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Dark Matter, Dark Energy: The Dark Side of the Universe

Course Guidebook

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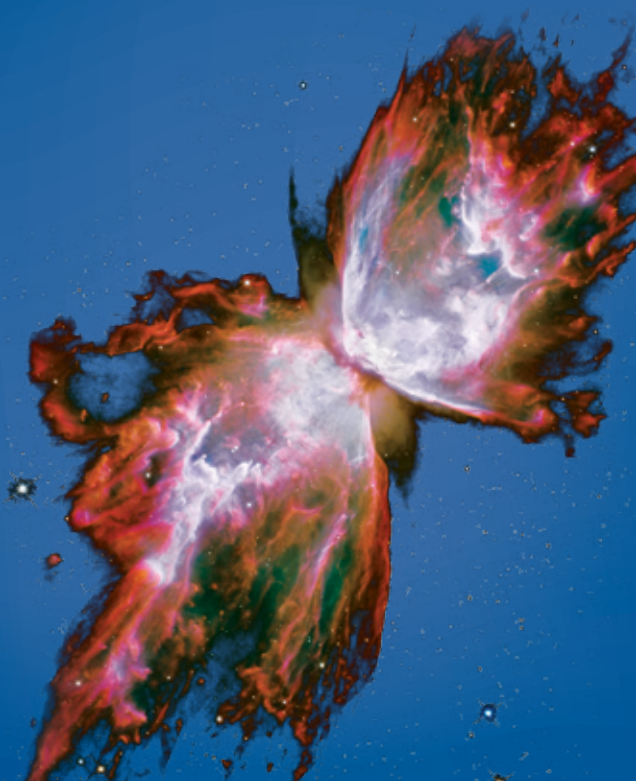

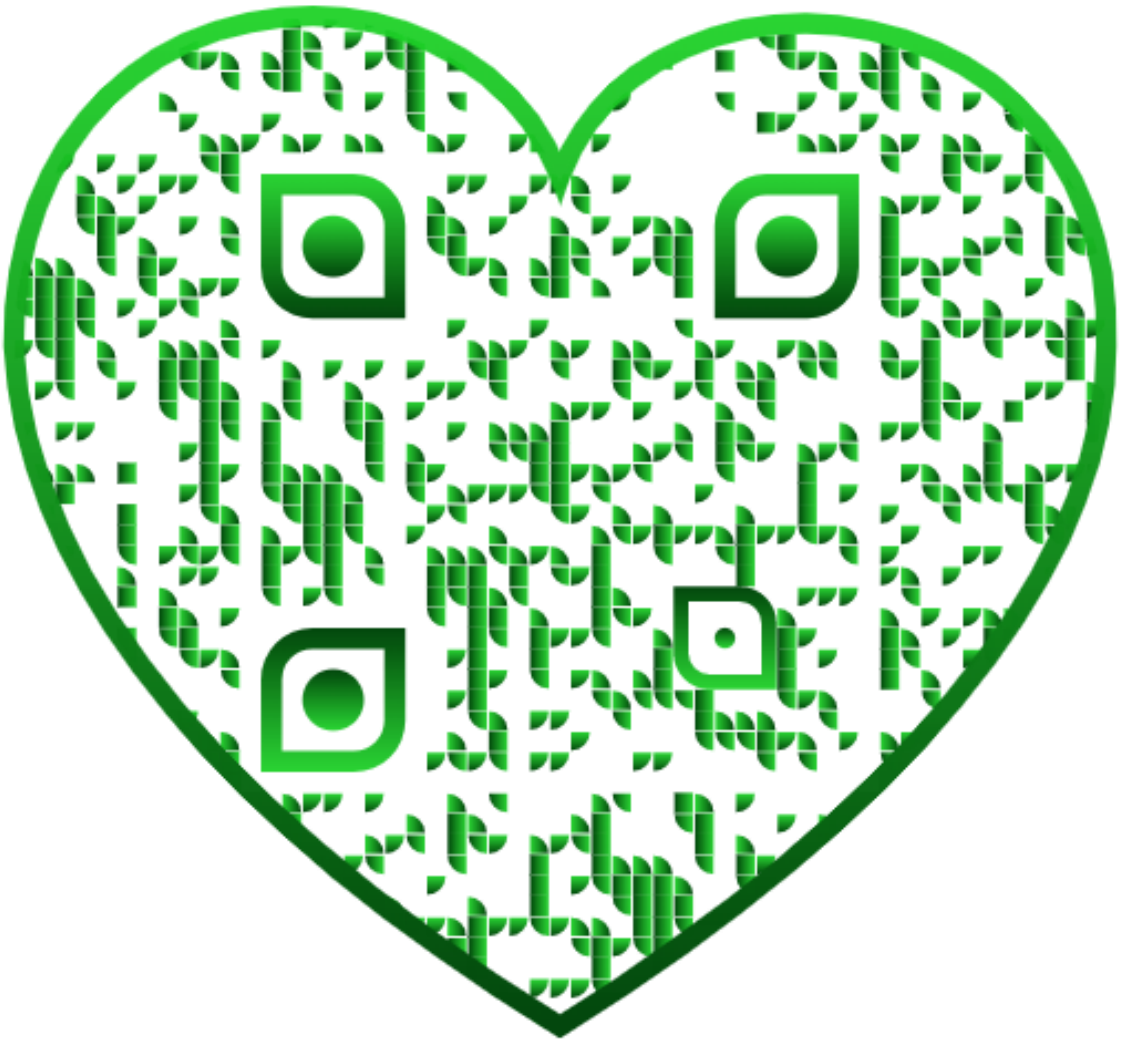

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Professor Sean Carroll is a Senior Research Associate in Physics at the California Institute of Technology. He did his undergraduate work at Villanova University and received his Ph.D. in Astrophysics from Harvard in 1993. His research involves theoretical physics and astrophysics, with a focus on issues in cosmology, field theory, and gravitation.

Prior to arriving at Caltech, Professor Carroll was on the faculty of the Physics Department and the Enrico Fermi Institute of the University of Chicago. Before that, he did postdoctoral research at the Massachusetts Institute of Technology and at the Institute for Theoretical Physics at the University of California, Santa Barbara. He has made contributions to the theories of topological defects, violations of spacetime symmetries, two-dimensional quantum gravity, anisotropies in the cosmic microwave background, models of brane worlds and extra dimensions, the origin of cosmological magnetic fields, causality violation in general relativity, and quantum supergravity. His current research involves models of dark matter and dark energy, cosmological modifications of Einstein's theory of general relativity, the physics of inflationary cosmology, and the origin of time asymmetry.

While at MIT, Professor Carroll won the Graduate Student Council Teaching Award for his course on general relativity, the lecture notes of which were expanded into the textbook *Spacetime and Geometry: An Introduction to General Relativity*, published in 2003. He has received research grants from NASA, the U.S. Department of Energy, and the National Science Foundation, as well as fellowships from the Sloan and Packard foundations. He has been the Malmstrom Lecturer at Hamline University, the Resnick Lecturer at Rensselaer Polytechnic Institute, and a National Science Foundation Distinguished Lecturer. In 2006 he received the Arts and Sciences Alumni Medallion from Villanova University.

Professor Carroll is active in education and outreach, having taught more than 200 scientific seminars and colloquia and given more than 50 educational and popular talks. He has written for *SEED*, *Sky & Telescope*, *Nature*, *New Scientist*, *The American Scientist*, and *Physics Today*; been interviewed by NPR, the BBC, and various local TV and radio programs; and been quoted in *Time*, *U.S. News and World Report*, *Scientific American*, *The New York Times*, *USA Today*, the *Boston Globe*, the *Chicago Tribune*, and numerous other newspapers and magazines. ■

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Dark Matter, Dark Energy: The Dark Side of the Universe

Scope:

For the first time in human history, we know what the universe is made of. A series of remarkable observations at the close of the 20th century enabled cosmologists to discover a complete inventory of the universe: about 5 percent *ordinary matter* (atoms, stars, galaxies), 25 percent *dark matter* (some new particle that hasn't yet been detected here on Earth), and 70 percent *dark energy*. The dark energy is something completely new and unexpected: a kind of energy density that seemingly exists even in completely empty space. Together, the dark matter and dark energy hold the key to the ultimate fate (and, possibly, the origin) of our universe.

This course will examine why we think that dark matter and dark energy must exist and what they might be telling us about the mysteries of fundamental physics. We will start with the picture of our universe that cosmologists constructed over the course of the 20th century. Our universe is big: It consists of billions of galaxies, each containing billions of stars, scattered nearly uniformly throughout space. And it's getting bigger: Galaxies are moving apart from each other as the space between them expands. The entire picture is accurately described by general relativity, Einstein's dramatic theory of spacetime and gravitation.

Gravity rules the cosmos on very large scales, and we can use it to probe the ingredients that compose the universe. Even if we don't see something directly, it will still give rise to a gravitational field. Following this logic, the motions of galaxies imply the need for more matter than we see directly: We call the extra stuff *dark matter*. We might suspect that the dark matter is just ordinary matter that isn't emitting or absorbing light, but that possibility can be ruled out. Particle physics as we know it is summarized in the Standard Model, a triumphant theory that fits just about every experiment performed here on Earth. But there are no particles in the Standard Model that could describe the dark matter—it must be something new and undiscovered.

The biggest reason why dark matter can't be any particle we know comes from our picture of the very early universe. Tracing backwards in time toward the Big Bang, we infer that the universe went through a series of transitions during which particles came together or were torn apart, such as in the first few minutes of its history, when free protons and neutrons combined to form helium and other elements. We see the remnants of these transitions today, and they imply strict bounds on the amounts of ordinary matter present in the universe. We also see the cosmic microwave background, relic radiation from when the universe first became transparent. The tiny fluctuations in the temperature of this radiation are tied to the composition of the universe and provide additional evidence that dark matter is something new.

Even newer is dark energy—something that isn't made of particles at all but is smoothly distributed through space and slowly evolving (if at all) through time. The dark energy has dramatic effects on the dynamics of the universe: It affects the overall curvature of space and causes the expansion rate of the universe to accelerate. These effects have been observed, leaving little doubt that dark energy does exist. But what is it?

Fundamental physics offers a few possible candidates for the origin of dark energy, but none makes perfect sense to us. The simplest is vacuum energy, or the cosmological constant—an absolutely constant energy density inherent in spacetime itself. The idea of vacuum energy is quite natural, but its magnitude is not; if vacuum energy exists at all, it should be much greater than what we observe. Alternatively, cosmologists have imagined that dark energy arises from some new dynamical field dubbed *quintessence*. This possibility has the attractive feature of being experimentally testable; if dark energy is varying with time, future experiments can reveal it.

Despite multiple lines of supporting evidence, there is the more dramatic possibility that dark matter and dark energy actually do not exist, but that instead, we are being tricked by the behavior of gravity. Einstein's theory of general relativity has been very successful, but there remains the possibility that it is incomplete on the very largest distance scales. Physicists have been busily inventing alternative theories, but they are tightly constrained by experimental tests. They have also been trying to reconcile general relativity with the formalism of quantum mechanics, efforts that have given rise to the

ideas of string theory. Although experiments to verify string theory haven't yet been devised, string theory holds out the intriguing possibility that the part of the universe we see is highly atypical—that we live in a tiny corner of a multiverse in which the local laws of physics are determined by their hospitability toward life as much as by deep, underlying principles.

Clearly, the challenges raised by dark matter and dark energy are pointing physicists and astronomers far beyond their current theories. Only an ambitious program of future observations and experiments will give us the necessary clues to build a comprehensive model that explains all of the dark side of the universe. ■

Fundamental Building Blocks

Lecture 1

When the universe was young enough, it was opaque; you couldn't see your hand in front of your face, imagining that you were there at the very early universe. But, when it was about 400,000 years after the Big Bang, it became transparent.

In recent years, scientists have achieved something remarkable: They have arrived at a complete inventory of the universe. Human beings have been wondering about the composition of the universe since ancient times, when they described substances as consisting of earth, air, fire, or water. Our modern equivalent includes *ordinary matter* (every kind of matter ever directly observed), *dark matter* (some kind of massive particles yet to be directly detected), and *dark energy* (a smooth component that remains persistent as the universe expands). Over the course of these lectures, we will see how this picture has been painstakingly developed through a series of increasingly precise observations of far-flung corners of the universe. Then, we can begin to dig more deeply, asking about the origins of these components and their explanations in fundamental physics.

Over the past few years, physicists and astronomers have pieced together, for the first time, a comprehensive picture of what the universe is made of. The answer seems to be that only 5 percent of the universe is made of ordinary matter, with 25 percent being some kind of unseen dark matter and a full 70 percent being a smoothly distributed dark energy. The purpose of this course is to explain what those things are and why we believe in them.

It is a profound idea that only a few kinds of things are needed to make up the infinite variety that we see. Although it's far from obvious, ever since the time of the ancient Greeks, we've been trying to explain the wonderful variety of nature by imagining some small set of basic substances that combine in different ways. The ancient Greeks famously suggested that earth, air, fire, and water were the "elements" that make up all the substances we see.

The modern version of this idea can be found in particle physics. The ordinary materials with which we are all familiar are made of *atoms*. This is also an old idea, but now we have a specific picture of what atoms are: small, massive, positively charged *nuclei* surrounded by even smaller, less massive, negatively charged *electrons*. Digging deeper into the atom, we find a new layer of structure: Nuclei are made of positively charged particles called *protons* and uncharged particles called *neutrons*. Digging still deeper yet, we find that protons and neutrons are, in turn, made of even smaller particles called *quarks*. Two different kinds of quarks, called simply *up* and *down*, combine in different ways to make protons and neutrons. How do we know? Particle physicists have uncovered the basic structure of ordinary matter through experiments at particle accelerators. These giant machines smash together particles at incredible energies, revealing new particles and further layers of structure.

These giant machines smash together particles at incredible energies, revealing new particles and further layers of structure.

Particle accelerators put us in touch with matter here on Earth, but we should be open to the possibility that the rest of the universe contains things that we don't directly observe in the lab. Ever since Galileo, telescopes have been our basic tools for observing the universe. These days, modern technology has given us more powerful instruments than Galileo could have possibly imagined. We have telescopes in orbit and here on Earth, looking at elementary particles, as well as at light in every conceivable wavelength. There might be "stuff" out there that isn't directly visible. But we have a way of inferring that it is there, through the existence of gravity. Everything in the universe creates a gravitational field, whether it's visible or not. The existence of dark matter and dark energy has, in fact, been inferred through our discovery of the gravitational fields they create. This seems fairly indirect, but as we'll see, the evidence is extremely strong. The next step is to detect them more directly, which is an ongoing research project.

Why should we care? Asking what the universe is made of is the quintessential example of basic research for its own sake. It has no practical purpose in terms of technology or economic benefit. Of course, research into

basic questions tends to produce practical benefits, whether we plan on them or not, but those are a bonus, not the primary motivation. We really ask these questions just because we're curious about the answers.

Although the story of dark matter and dark energy makes a lot of sense, in another sense it is also very surprising; as mentioned in this lecture, it is helpful to hear the same story over and over again, so it can really sink in. Here is a broad overview of how we'll proceed in this course. First, we will look out at the universe and ask what we can see directly. Then, we will take a step back, thinking about how space and time work, as well as how particle physics works. We will then apply these ideas to cosmology and the early universe. Our exploration will lead us to believe in dark matter and dark energy. The dark energy is especially a mystery, and we'll talk about what it might have to teach us about fundamental physics. Because these ideas are at the forefront of current research, we'll conclude with discussion of the prospects for the future, both in terms of experimental efforts and theoretical ideas. ■

Suggested Reading

Hogan, *The Little Book of the Big Bang*, chapters 2–3.

Weinberg, *Dreams of a Final Theory*, chapter 2.

Questions to Consider

1. In your own view, why is it interesting to study the structure of the whole universe? How would you explain that interest to someone else?

2. Should it be surprising that cosmology, the study of the very largest things, is intimately connected to particle physics, the study of the very smallest?

3. Cosmologists believe that most of the universe is made of substances utterly different than the atoms and particles with which we are familiar. How do you feel about that? Again, should we be surprised?

Similarly, the other analogy that is very famously used is raisin bread. You start with a lump of raisin bread dough, with raisins inside. You put it in the oven, and the bread expands, as perhaps you know, the raisins move away from each other and people go, there you go, it's like the expanding universe.

Whenever anyone tries to explain modern cosmology, the first step is usually to introduce a bad analogy: The universe is a loaf of raisin bread or an expanding balloon. Rather than invoking an analogy, we consider the actual universe. Imagine standing outside on a perfectly clear night and imagine that you have impossibly perfect vision. What would you see? The first things you would notice are the Moon, planets, and stars. The Sun is just a star itself, but one that seems much brighter because it's much closer to us. We live in a Solar System in which the planets (including Earth) orbit the Sun, and the Moon orbits the Earth, just as other satellites orbit other planets. If you look closely, you would notice a cloudy band stretching from one horizon to the other: the Milky Way. Careful inspection reveals that the Milky Way is itself a collection of stars—about a hundred billion of them, if you were to count. They orbit around each other very slowly. We call such a collection of stars a *galaxy*.

NASA.

The Andromeda galaxy is a collection of 100 billion stars orbiting under their own mutual gravitational attraction.

Although it is not obvious merely from looking at the sky, our galaxy is one of many. For a while, it was thought that we lived in an "island universe"—the Milky Way was surrounded essentially by empty space. But we knew that not everything in

the sky was a star; stars appeared as points, but there were also fuzzy patches known as *nebulae*. Some people suggested that some nebulae were galaxies themselves, but this was a controversial claim. The debate was settled by Edwin Hubble, who in 1925 showed that many nebulae are far outside the Milky Way. At least some of the nebulae are galaxies in their own right; others, as it turns out, really are clouds of gas and dust within our galaxy.

A fundamental challenge in astronomy—exacerbated by the discovery of galaxies beyond our own—is figuring out how far away objects are from us. An object whose intrinsic brightness is known can be used as a *standard candle*. If we measure how bright the standard candle appears, we can deduce how far away the object must be. An example of a standard candle is given by a particular kind of star known as a *Cepheid variable*. Cepheids are pulsating stars, and in 1908, Henrietta Leavitt showed that their period of pulsation is directly tied to their brightness. They provide a unique method for determining distances out to cosmologically interesting scales.

Deeper inspection of the universe reveals that it is full of galaxies—perhaps a hundred billion in observable space, comparable to the number of stars in a single galaxy. Modern images show us that there is an astonishing variety of galaxies everywhere we look, scattered almost uniformly throughout the universe.

Knowledge about other galaxies quickly led to the insight that the universe is expanding. One way to measure the motion of an object is to observe the *Doppler effect*. Both light and sound, the two easiest ways to detect objects, come to us in the form of *waves*, and each wave has a definite *wavelength*. Longer wavelengths correspond to lower frequencies; for sound, low frequency means a deeper pitch, while for light, low frequency is red and high frequency is blue. If an object is in motion as it emits waves, the waves are distorted: They get squeezed into shorter wavelengths when coming toward us and stretched to longer wavelengths when moving away. The Doppler effect applies just as well to galaxies as it does to trains going by. (Actually it doesn't, strictly speaking. As we'll discuss later, wavelengths are stretched by the expansion of space, not by any real motion of galaxies. But it's useful to think of it that way for right now.) Vesto Slipher demonstrated

that almost all galaxies are redshifted, implying that they are moving away from us.

Not only are galaxies redshifted, but in 1929, Hubble and Milton Humason discovered that the amount of redshift increases with the distance to the galaxy. *Hubble's Law* says that the apparent recession velocity is directly proportional to the distance: $v = Hd$. The constant of proportionality, which tells us how fast the universe is expanding, is usually called the *Hubble constant*. It's not really constant, however, given that it was certainly larger in the early universe; sometimes, we are more careful and call it the *Hubble parameter*. Recent observations by Wendy Freedman and collaborators have shown that the Hubble parameter today is 72 kilometers per second per megaparsec. Thus, for every 1 million parsecs of distance, we observe a galaxy to be moving with a velocity of 72 km/sec.

A profound implication of Hubble's result is that observers in any galaxy would see almost every other galaxy as moving away from themselves.

A profound implication of Hubble's result is that observers in any galaxy would see almost every other galaxy as moving away from themselves. We could mistakenly get the impression that we are at the center of the universe because everything else is racing away from us in every direction. But from the point of view of another galaxy, we are racing away. There is no center to the universe; every cosmological location is pretty much created equal. Not only is there no center, but there is nothing outside the universe. Even though the universe is expanding, it's not expanding *into* anything—there's just more of it. This is a profound notion, and to really understand it, we'll need to delve into Einstein's theory of general relativity, which we'll discuss in the next lecture.

As a whole, the universe is smooth. When we look at galaxies in the universe, their distribution seems clumpy at first; they tend to group into clusters. But if we take a broad enough viewpoint, the average number of galaxies in any one direction of the sky is pretty much the same as in the other directions. In other words, the universe looks the same in every direction.

Although the universe is basically the same on sufficiently large scales, it's noticeably non-uniform on smaller scales. As we will discuss later, things were even smoother in the early universe, although there were always tiny deviations from perfect smoothness. These deviations grew as the universe expanded, leaving behind the interesting pattern of clusters and large-scale structure that we see in the distribution of galaxies today. ■

Suggested Reading

Ferris, *The Whole Shebang*, chapter 2.

Hogan, *The Little Book of the Big Bang*, chapter 4.

Kolb, *Blind Watchers of the Sky*, chapters 6–7.

Overbye, *Lonely Hearts of the Cosmos*, chapter 3.

Questions to Consider

1. Imagine that you are an ancient astronomer, looking at the night sky without any instruments. How would you estimate the distance to the planets and stars?

2. Think about how analogies and metaphors are useful or misleading when it comes to the whole universe. Can you think of any good analogies?

3. How does the cosmological principle compare to Copernicus's original insight that the Earth is not at the center of the Solar System? Can you extrapolate this Copernican philosophy to other questions?

Space, Time, and Gravity

Lecture 3

The absolute fact that a certain object is a certain length, is going to turn into a relative in relativity.

Special relativity replaces the absolute space and time of Newton with a single unified notion of spacetime. The first person to come up with a comprehensive picture of space and time was Isaac Newton. In his view, space and time were absolute, indelible features of the universe, set down once and for all. Two people, equipped with clocks and meter sticks, would always measure the same intervals of time and space between two events. Einstein's thinking changed all that. To make a long story short, Einstein realized that time was like space; indeed, the two of them were married together in a single notion of *spacetime*. There is no universal, absolute distinction between "time" and "space" that would be agreed upon by all observers.

To make this abstract idea more concrete, think of two different paths in space that connect the same two points: One is a straight line, while one is curved. Clearly, the distance you would travel by moving along these two paths is different, even though they connect the same points. Einstein realized that time is like that: The time elapsed on your watch is not absolute, as it would be for Newton, but depends on the path you take through spacetime. In Einstein's universe, time is personal—a fact of what you do, not a fact of the universe.

General relativity gives spacetime a geometry that can warp and bend through time; we interpret the effect of spacetime's geometry as the force of gravity.

Einstein's new theory of spacetime is known as *special relativity*. But just because time and space are no longer absolute doesn't mean that the universe has no laws. The fixed slicing of spacetime in Newton's framework is replaced by a fixed speed limit: Nothing can go faster than the speed of light. At any point in space, we can consider

the set of all possible paths that light could take; these define a *light cone* that tells us once and for all which trajectories are possible and which ones are impossible.

General relativity gives spacetime a geometry that can warp and bend through time; we interpret the effect of spacetime's geometry as the force of gravity. Special relativity provided a fundamentally new framework for physics, one that was perfectly compatible with the laws of electricity and magnetism. It was not, however, compatible with Newton's other famous theory, the law of gravitation. Einstein embarked on a quest to reconcile relativity with gravity as we know it.

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Newton is depicted contemplating gravity under the infamous apple tree.

Eventually, Einstein realized something profound: Gravity, unlike the other forces of nature, is universal. This is an idea that goes all the way back to Galileo; gravity works in exactly the same way on everything. If this is true, Einstein reasoned, maybe we shouldn't think of gravity as a force at all; instead, we can think of it as a feature of spacetime itself. Einstein's work culminated in 1915 in the theory we know as *general relativity* (GR). GR is an extension of special relativity, but it allows spacetime to be curved, and it is this curvature (geometry) of spacetime that we experience as gravity. General relativity comes along with one master equation, known simply as *Einstein's equation*: $R_{\mu\nu} - (1/2)Rg_{\mu\nu} = (8\pi G)T_{\mu\nu}$. Don't worry about the details! The left-hand side represents the curvature of spacetime, while the right-hand side describes the properties of stuff in the universe—mass, energy, and momentum.

The special feature of gravity is that it acts universally on all forms of matter and energy. Einstein realized that everything responds to gravity in the same way; conversely, everything that exists gives rise to some sort of

gravitational field. This provides a unique way to probe the universe: Look for gravitational fields. Wherever something is, it must create some sort of gravity. As we shall see, this is exactly the technique that allows us to infer the existence of dark matter and dark energy. As a bonus, the dynamical nature of spacetime allows us to ask questions that would have been unthinkable in a Newtonian framework, such as: Where did the universe come from? According to Newtonian absolute space, the universe was simply always here, unchanging. But Einstein's universe evolves and grows. We don't yet know the answer to profound questions such as these, but Einstein's theory allows us at least to ask them. ■

Suggested Reading

Greene, *The Fabric of the Cosmos*, chapter 3.

Osserman, *Poetry of the Universe*.

Randall, *Warped Passages*, chapter 4.

Wald, *Space, Time, and Gravity*, chapters 1–3.

Questions to Consider

1. What does it mean for two distant events to happen "at the same time"? Is this a concept that we can really afford to do away with?

2. Imagine a careful experiment showing that two objects fell at slightly different rates in a gravitational field. How would you interpret that result?

3. Einstein was a popular icon, as well as a leading scientist. Do you think he deserved his special status in the popular imagination?

Cosmology in Einstein's Universe

Lecture 4

The first reason is the universe has a finite age, at least since the Big Bang. For reasons that we'll talk about later, the time between now and the Big Bang is fairly well determined to be about 14 billion years.

In this lecture we combine the previous two lectures: we take the idea of a smooth, expanding universe—a universe that is the same everywhere throughout space, but growing as a function of time—and understand it in the context of general relativity. Observational evidence, plus the philosophy of the cosmological principle, leads us to believe that the distribution of matter in the universe is pretty much the same everywhere, at least on small scales. According to Einstein, that implies that the curvature of spacetime should be pretty much the same everywhere. The large-scale universe, at any one moment in time, is a pretty simple place.

Although the universe is homogeneous in space, it does seem to be evolving with time; in fact, it's expanding. Earlier, we spoke about this expansion as if galaxies were moving away from us, and the light from them was redshifted by the Doppler effect. General relativity provides a more sophisticated viewpoint. We think of galaxies as basically sitting at the same place in space (apart from some local motions), but the space itself in between the galaxies is expanding! The reason that light is redshifted as it gets to us is not because the galaxies are "moving away," but because the expanding space is stretching the waves as they travel.

We don't know how big space is—it could be infinite, or it could be finite. But we know the relative size of space at different moments in time. We invent a quantity called the *scale factor*, which tells us how much the universe has expanded between any two moments. When the scale factor was one-half, all the galaxies in the universe were half their current distance apart from one another. When the scale factor is two, everything will be twice as far apart as it is now. It's important to consider what happens to light and matter in the universe as space expands. Light gets redshifted, which implies that each individual photon loses energy. At the same time, matter and radiation both

get diluted; at earlier times, they were squeezed together in a highly dense state, but in time, they grow less and less dense.

Cosmologists distinguish between *matter*—made of particles that are moving slowly compared to the speed of light—and *radiation*—both light itself and any other kind of particle that moves at the speed of light. Because radiation moves at the speed of light, its mass is zero, and its energy comes, not from $E = mc^2$, but from the frequency at which it vibrates. As the universe expands, the frequency of radiation decreases: the energy in each particle of radiation dips down. Meanwhile, the energy in each particle of matter is a constant, given by the famous formula $E = mc^2$. Therefore, the total energy density in radiation dilutes away more quickly than that in matter. The early universe—the time before a great deal of radiation diluted away—was dominated by radiation. In other words, in the early universe, radiation, rather than matter, was important for the expansion of the universe.

In the simple case of a smooth, expanding universe, the curvature of spacetime divides neatly into two separate contributions: the expansion of space as a function of time and the curvature of space itself. This is one time when analogies are useful. In two dimensions, zero curvature is just a *flat plane*; geometry works just as it did for its inventor, Euclid. But we could also imagine living on the surface of a two-dimensional sphere; there, unlike on a plane, parallel lines would eventually intersect. We call such a geometry *positively curved.* We could also imagine the surface of a saddle, on which parallel lines would diverge—that's *negative curvature*.

The possibilities of positive and negative curvature generalize to the three-dimensional space in which we live. In fact, Carl Gauss, the mathematician who first delved deeply into curved geometries, tried to search experimentally for spatial curvature. Gauss set up surveying equipment to measure the angles inside a really big triangle. He found, to the precision available with his instruments, that space is flat. These days, we have much better instruments, but as we will eventually see, it still seems as if space (not spacetime!) is flat.

Energy drives the expansion of the universe. At any one moment, our simple, smooth universe is characterized by three numbers: the expansion

rate (measured by Hubble's constant), the energy density, and the curvature of space. Einstein's equation of general relativity provides us with a unique relationship among these quantities; if we know two of them, Einstein will tell us the third. The specific application of general relativity to the situation of a uniformly expanding universe is known as the *Friedmann equation*, after Russian mathematician Alexander Friedmann: $(8\pi G/3)\rho = H^2 + K$. Here, ρ is the energy density, H is the Hubble parameter, and K is the curvature of space, but again, don't worry about the details; just appreciate that the energy density of the universe (the number of ergs per cubic centimeter in every little part of the universe) is what drives the curvature of space.

These days, we have much better instruments, but as we will eventually see, it still seems as if space (not spacetime!) is flat.

General relativity doesn't just relate these numbers (energy density, expansion rate, and curvature of space) at each moment in time—it tells us how they change with time. In particular, it allows us to determine how the scale factor evolves. The universe is currently expanding; in the past, it was much smaller, and we can extrapolate from our current conditions all the way back to the earliest times in history of the universe. We can use that extrapolation to make predictions about what the universe looks like right now—and those predictions turn out to be true. ■

Suggested Reading

Ferris, *The Whole Shebang*, chapters 2–3.

Hogan, *The Little Book of the Big Bang*, chapter 4.

Nicolson, *The Dark Side of the Universe*, chapter 2.

Weinberg, *The First Three Minutes*, chapter 2.

Questions to Consider

1. Is there really a difference between light being redshifted by the Doppler effect or by the expansion of space? Can you think of examples to illustrate whether such a difference really exists?

2. Adding up the angles inside a triangle is one way to measure the curvature of space. Can you think of others?

3. How would you test the Friedmann equation experimentally?

Galaxies and Clusters

Lecture 5

The universe is smooth on very large scales and this is an incredibly helpful feature as far as cosmologists are concerned because that means that we can approximate the universe as being absolutely smooth, and that's exactly what we did.

Having emphasized that the universe on large scales is very smooth, it's now time to face up to the fact that on smaller scales (cosmologically speaking), it's not smooth at all. We believe that the very early universe was smooth on all scales. Strong evidence for that belief comes from the *cosmic microwave background* (CMB). Because the early universe was so dense and hot, it emitted radiation copiously. We can see that radiation today, redshifted into the microwave region of the electromagnetic spectrum. That's the CMB, which we'll discuss in detail in Lecture 11. The important point now is that the CMB provides us with a snapshot of the early universe, and it is extremely smooth. Differences in temperature from place to place are no more than 1 part in 100,000.

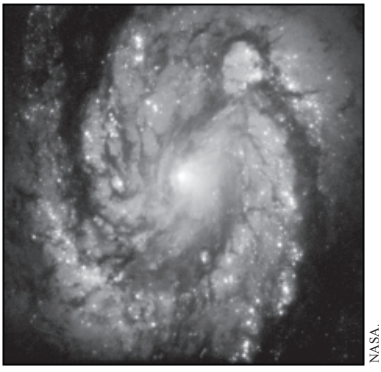
We can count stars in galaxies, but how do we know that what we see is all there is?

But as the universe expanded, gravity got to work on the slight ripples in density. If a region had somewhat more than the average number of particles, gravity pulled them together even more tightly. By this mechanism, the "contrast knob" on the universe was gradually turned up as the universe expanded. The tiny deviations from perfect smoothness in the early universe grew under the force of gravity into stars, galaxies, and clusters of galaxies. Because matter moved slowly, smaller objects formed first. It took billions of years for stars to form, and they gradually accumulated into larger structures that we can see today.

Galaxies—the basic unit into which matter organizes itself on large scales—suggest the existence of unseen matter. The most obvious collections of matter in the universe are galaxies. They are accumulations of stars, gas,

and dust, orbiting under their mutual gravitational pull. And they make for extremely pretty pictures!

We can count stars in galaxies, but how do we know that what we see is all there is? As we've discussed, one route to detecting everything is to measure gravity. We can "weigh" individual galaxies by asking how strong the gravitational field is in the vicinity of the galaxy. That can be measured by observing the speed at which gas and dust orbit the galaxy; the weaker the gravity, the more slowly we expect the gas and dust to move.


NASA.

Spiral Galaxy M100.

In the 1970s, Vera Rubin pioneered the measurement of *rotation curves* of galaxies—observations of the speed at which matter is orbiting the center of the galaxy as we move away from it in distance. This led to a surprising result: Distant matter is moving much faster than it should be! That is, given the gravitational field we would expect from the matter we observe in galaxies, the rotation speeds of dust particles should decline as we get further away from the galactic center. But that's not what happens; the rotation speed remains approximately constant, indicating that there is unseen matter giving rise to extra gravity.

Clusters of galaxies provide further evidence that unseen matter exists. Some galaxies are alone in the universe, but many are grouped together in clusters. If we point X-ray telescopes at clusters, we find that there is a great deal of gas in between the galaxies; in fact, most of the matter in a cluster is not in the galaxies themselves but in between.

Compared to galaxies, clusters tend to be messier and spherical, rather than organized into pretty disks. Nevertheless, we have ways of measuring the total amount of gravity and, hence, the total amount of matter in clusters. One way is to observe the X-ray gas, which settles into the gravitational field

and heats up accordingly. Another way is to measure the average velocity of galaxies in clusters.

Again, we find a surprising result: There is much more gravity in clusters of galaxies than can be accounted for by the "ordinary" matter (even including the X-ray-emitting intergalactic gas). This was actually pointed out long ago, by Caltech astronomer Fritz Zwicky in the 1930s. Ordinary matter just isn't enough to explain the discrepancy: We need dark matter.

From what we've said so far, all we can conclude is that we need more matter than we can detect directly. It could, in principle, be perfectly ordinary matter that simply takes some form that is hard to see, such as pebbles or dark gas. Later, we will give arguments that this actually isn't possible. Dark matter can't be ordinary; it must be some completely new kind of particle. ■

Suggested Reading

Ferris, *The Whole Shebang*, chapter 5.

Freeman and McNamara, *In Search of Dark Matter*, chapters 1–4.

Goldsmith, *The Runaway Universe*, chapter 6.

Questions to Consider

1. How could we, in principle at least, be sure that dark matter can't possibly be ordinary matter that is simply not visible for some reason?

2. Is it possible to "prove" that dark matter exists, at least beyond any reasonable doubt?

3. Can you think of hypothetical examples where we could detect dark matter or at least infer its existence without observing it directly? Do you always need to "see" something to know that it's there?

Gravitational Lensing

Lecture 6

So, what do you do when something moves in an orbit that is not quite what is predicted by Newton's Law of Gravity? You invent dark matter and that is, in fact, exactly what was done.

The evidence from dynamics that we need dark matter in galaxies and clusters is convincing, but the claim is sufficiently dramatic that we would like some form of confirmation. We turn to *gravitational lensing* as an alternative way to measure total mass. Part of general relativity is the idea that everything reacts to gravity in the same way. This includes, for example, light itself. A photon passing through a gravitational field will be deflected, just as it would if it passed through a lens made of glass. This is the phenomenon of gravitational lensing. Lensing was an early prediction of general relativity (GR), made by Einstein himself, and it led to one of the earliest experimental tests of the theory. The gravitational field of the Sun is fairly weak by astrophysical standards; nevertheless, it deflects light by a tiny angle. In 1919, Sir Arthur Eddington organized an expedition to observe the positions of stars near the Sun during a total solar eclipse. He found that they were deflected from their expected positions just as GR predicted. Announcement of this finding made Einstein an international celebrity. These days, we use lensing to measure the mass of objects. The more mass an object has, the more gravity it has, and the greater the deflection.

Lensing can be caused by galaxies and clusters. In cosmological contexts, gravitational lensing is roughly divided into two regimes: *weak* and *strong*. The dividing line between the two is whether light is deflected enough to create multiple images of the source (strong lensing) or just enough to distort the image of the source (weak lensing). Both are useful in astronomy. Strong lensing provides a fairly straightforward way to measure the mass of an object, whether it's a galaxy or a cluster. Just as a highly warped pane of glass will give rise to a highly distorted image when you look through it, a massive astronomical object will strongly lens any object in the background, and the separation of the multiple images tells us how much matter there is in the lens.

Weak lensing is more subtle. If, for example, a single galaxy is weakly lensed, we can't tell much about the amount of lensing, because we don't know much about what the original galaxy looked like. However, the method becomes extremely powerful once we have a large number of background objects being lensed. Then, we begin to see systematic correlations in the shapes and orientations of the lensed objects, caused not by intrinsic alignments but by the lensing itself. Cosmologists have now been able to apply these techniques to a number of clusters of galaxies, and they have found that dark matter is still needed. They have even been able to map out the distribution of dark matter in three dimensions, using the amount of lensing experienced by sources at different distances.

An optical image of the Bullet Cluster reveals that it's actually two nearby concentrations of galaxies in the sky.

Spectacular results from the Bullet Cluster in 2006 exemplify what lensing can tell us about dark matter. An optical image of the Bullet Cluster reveals that it's actually two nearby concentrations of galaxies in the sky. By taking redshifts, we can verify that the galaxies are actually physically close to each other. But a look at the X-ray gas reveals something interesting: Unlike what we find in ordinary clusters, the gas is not located in the same place as the galaxies. It's mostly in between the two clusters. There is a simple explanation for this: These two clusters collided with each other recently. The galaxies, which are much smaller than the clusters, simply went right through each other, but the intergalactic gas in each cluster interacted with the gas in the other, giving rise to a shock front. As a consequence, the gas (which is by far most of the ordinary matter in the clusters) was separated from the galaxies. Using lensing, we can measure the gravitational fields of the clusters. Computer reconstructions are able to create maps of the gravitational field, which reveal where most of the matter is.

For the Bullet Cluster, we see a remarkable result: The gravity (and, thus, most of the matter) is not where the gas is. It remains associated with the two groups of galaxies, even though there is less ordinary matter there than in the gas. Apparently, most of the total matter in the cluster is not gas at all—it's some kind of stuff that doesn't interact, doesn't collide with other particles, but rather, goes right through them. That stuff, of course, is dark matter. ■

Suggested Reading

Freeman and McNamara, *In Search of Dark Matter*, chapter 7.

Goldsmith, *The Runaway Universe*, chapter 13.

Hogan, *The Little Book of the Big Bang*, chapter 6.

Questions to Consider

1. Ordinary lenses can be convex or concave. What would be the analogous property of gravitational lenses? What would that imply about the matter that was creating the gravitational field?

2. Imagine that we didn't know about the Bullet Cluster. Could you think of a way to tell the difference between dark matter and some unexpected property of gravity?

Atoms and Particles

Lecture 7

Electrons are very light elementary particles. As far as we know or even in the context of our best theories, electrons really are indivisible. No one has a good model for how an electron could have stuff inside it.

To understand dark matter, we should make an effort to understand ordinary matter first. Such an understanding begins with atoms. We've already discussed the basic structure of atoms. Electrons orbit around a compact nucleus, which is made of protons and neutrons. These protons and neutrons (known collectively as *nucleons*) are, in turn, composed of up and down quarks. Electrons have electric charge –1, protons have charge +1, and neutrons have charge 0. Up quarks have charge +2/3, while down quarks have charge –1/3. These basic particles—electrons, up quarks, and down quarks—are all the matter needed to make up our everyday world.

But these matter particles wouldn't arrange themselves into the configurations they do—nucleons, nuclei, atoms, molecules, and so on—if it weren't for another kind of particle, force-carrying particles that bind them together. We've already mentioned in passing one kind of force-carrying particle, *photons*, which carry the electromagnetic force. Photons are what hold electrons together with atomic nuclei. There are also *gluons*, which carry the strong force; gluons are what hold quarks together in nucleons.

There are two basic types of particles: bosons and fermions. The dichotomy between matter particles and force particles is the most basic feature of the subatomic world. Matter particles are known formally as *fermions*, after Enrico Fermi; quarks and electrons are examples. The characteristic feature of fermions is that they take up space—you can't simply pile a bunch of fermions on top of each other in the same place. More formally, the *Pauli exclusion principle* says that no two fermions can be in the same state (in the same place doing the same thing at the same time). That's a welcome feature, because without it, every structure that we know of would simply collapse in on itself.

Force-carrying particles are called *bosons* after Satyendra Nath Bose; photons and gluons are examples. Unlike fermions, bosons can pile up on top of each other, which is exactly what happens when we observe a macroscopic force field, such as an electric or magnetic field. Such a field is a large number of bosons, each contributing just a little bit, that combine to create a noticeable amount of force. One of the great conceptual unifications of physics is the realization that photons, in various configurations, can account for so much—electric and magnetic fields, light waves and other forms of electromagnetic radiation, as well as radiative heat.

We can safely say, however, that the dark matter certainly isn't antimatter; if it were, it would be constantly colliding with ordinary matter, annihilating and creating very visible radiation.

Each kind of elementary particle has a *spin*, a certain fixed amount of angular momentum. Spin is another way of distinguishing between fermions and bosons. Every boson has an integer spin (such as 0, 1, 2...), while every fermion has a spin that is always a half integer (such as 1/2, 3/2, 5/2...). Electrons and quarks, for example, are spin 1/2, while photons and gluons are both spin 1.

Finally, in addition to matter, there is also *antimatter*. As we'll see, antiparticles are, in some sense, particles moving backwards in time. Fermions generally have distinct antiparticles, with the feature that a particle and an antiparticle can come together and annihilate into energy. The antiparticle of the electron, for example, is called the *positron.* An electron and a positron can collide to create photons. Bosons, on the other hand, are often their own antiparticles. For some reason, there is a lot more matter in the universe than antimatter; that's one of the many mysteries we won't have time to delve into in this course. We can safely say, however, that the dark matter certainly isn't antimatter; if it were, it would be constantly colliding with ordinary matter, annihilating and creating very visible radiation.

Even within the atom, particles are held together by other particles. Quarks are held together by gluons to form protons and neutrons. But what holds

protons and neutrons together? That's actually a complex question, but the rough answer is *pions*—a kind of boson that itself is made of two quarks (in fact, a quark-antiquark pair). Electrons, as we've mentioned, are bound to atomic nuclei by photons. Photons also do the work of binding atoms together to make molecules; atoms stick to each other because of the stray electromagnetic fields in the individual atoms.

There is another well-known force, of course: gravity. As you might expect, we believe that gravity is carried by particles called *gravitons*. We have never observed individual gravitons because the force of gravity is too weak; we've observed only the macroscopic collections of gravitons that make measurable gravitational fields. We do, however, believe that gravitons exist.

Particles can interact with each other in various ways. Particles are classified by whether they are bosons or fermions, what their mass is, and how they interact with other particles. These interactions can be pictured using *Feynman diagrams*, (such as the one we see showing an electron emitting a photon and going along its way). A nice feature of such diagrams is that we can switch particles from the right side to the left, at the same time, turning them into their antiparticles. A photon, for example, is its own antiparticle, so we also have a diagram showing an electron absorbing a photon. A positron can be thought of as an electron going backward in time—the same diagram that shows an electron emitting a photon can be used to describe an electron and a positron (the antielectron) annihilating into a photon. Not every particle interacts with every other one. Electrons, for example, do not interact with gluons. Photons do not interact with themselves, but gluons do interact with other gluons. ■

Suggested Reading

Hogan, *The Little Book of the Big Bang*, chapter 3.

Randall, *Warped Passages*, chapter 7.

Questions to Consider

1. The ancient Greeks believed in "atoms," although they didn't know anything about particle physics. Why might they have come up with that idea?

2. Whenever we investigate further, we tend to find new layers of structure in matter. Do you think these layers will ever end? Will we discover the ultimate building blocks?

The Standard Model of Particle Physics

Lecture 8

The neutron is a heavy particle made of two down quarks and one up quark, but it's unstable. The neutron left by itself will decay with a lifetime of about 10 minutes.

We can now be a little more systematic about the entire set of particles and forces that physicists have discovered in their laboratories. Together, this structure forms an extremely successful theory, known by the unimaginative name of the *Standard Model of Particle Physics*. Part of the point of this lecture will be to check that none of the known particles in the Standard Model is a good candidate for dark matter. Before going into details, let's get the basic idea. There is a kind of light, neutral fermion called the *neutrino*. This neutrino, together with the electron and the up and down quarks are four fermions that form a single *family* or *generation*. There are three such families, each with two quarks (fermions that feel the strong nuclear force) and two *leptons* (fermions that don't feel the strong nuclear force).

The bosons of the Standard Model come in five types. Three of these are well understood: the photon associated with the electromagnetic force; eight types of gluons associated with the strong force; and three bosons, the W^+, the W^-, and the Z, associated with something called the weak nuclear force. There is also a Higgs boson, which hasn't yet been discovered, and the graviton, which sometimes is not included in the Standard Model because we don't yet understand quantum gravity.

So, as just mentioned, fermions come in three families. [See the appendix entitled "The Standard Model of Particle Physics."] We only need three fermions to account for everyday objects: the up quark, the down quark, and the electron. But there is only one electron compared to two kinds of quarks; that hardly seems fair. In fact, there is another kind of particle that is similar to the electron but is much harder to detect because it has 0 charge (and, therefore, doesn't couple to photons): the *neutrino*. Quarks interact

with gluons and are confined inside other particles, such as nucleons and pions. Electrons and neutrinos, in contrast, don't interact with gluons and can propagate freely by themselves. Together, the electron and the neutrino are known as *leptons*.

Because neutrinos don't interact either with gluons or with photons, they don't stick together to make up solid objects, but they can be formed in certain kinds of nuclear reactions. In particular, the neutron is a little bit heavier than the proton, and left by itself, a neutron will decay into a proton (in about 10 minutes). In the process of doing so, the neutron emits an electron and an anti-neutrino. In fact, this process of decay was how neutrinos were first discovered: For nuclear decays to be consistent with the principle of conservation of energy, Wolfgang Pauli suggested that an invisible particle was being emitted. These days, we are very good at detecting neutrinos directly. We used to think they were massless, but recent experiments prove that neutrinos do have a small, nonvanishing mass.

The search for the Higgs boson is one of the highest priorities of experimental particle physics; by the time you read this, it may already have been found!

The neutrino almost has the right properties to be a good dark matter candidate—it is stable, neutral, and weakly interacting. But we'll see that, when we look at the details, neutrinos don't quite work as dark matter because their masses are too small. It's not that neutrinos can't give us the right total density; it's that individual neutrinos are nearly massless and move very quickly, zipping right out of galaxies rather than settling into them.

You might think that these two pairs of fermions, two quarks and two leptons, really are all you need, and it's hard to see why you'd be wrong. However, nature provides us with more than we need: This 2 + 2 pattern is repeated three times! There are actually six kinds of quarks and six kinds of leptons. The extra quarks are called *strange*, *charm*, *bottom*, and *top*. The extra leptons are the *muon* and the *tau*, which are like heavier versions of the electron, and two more versions of the neutrino, known as the *muon neutrino*

and the *tau neutrino*. Once all this was figured out, the original neutrino was renamed the *electron neutrino*. The way we can distinguish them is that electron neutrinos interact with electrons but not with muons or taus, and so forth. The extra families (or *generations*) of fermions are heavier than the first one and tend to decay into them (except for the neutrinos, which we haven't measured very precisely just yet). That's why these fermions don't appear as part of everyday objects.

There are five forces that act on fermions. Photons are the carriers of the electromagnetic force. Any particle that has an electric charge is one that feels the electromagnetic force; the electron has charge −1, while the up quark has charge +2/3 and the electron neutrino has charge 0. Interestingly, the photon has 0 charge itself, so photons don't interact directly with each other.

Gluons are carriers of the *strong nuclear force* (which binds quarks together). Gluons, like photons, are spin 1. There are actually eight types of gluons, but we don't need to go into the details of them here. The important point to note here is that the strong force is strong and leads to something called *confinement*. This simply means that particles that interact with the strong force—quarks and gluons themselves—get bound so strongly to other particles that they can never be seen by themselves but only when bound together as *hadrons*. Hadrons come in two varieties.

We assign three different colors to quarks—red, green, and blue—and corresponding anti-colors to antiquarks. The rule is, then, that only colorless combinations exist as physical particles. We can, therefore, have collections of three quarks; these hadrons are known as *baryons*: red plus green plus blue makes white. Protons and neutrons are both baryons. We can also have combinations of a single quark and a single antiquark with the opposite color; these hadrons are known as *mesons*. Pions are a good example.

There is also, as you may have guessed, a *weak nuclear force*. This is carried by two kinds of bosons: neutral *Z-bosons* and electrically charged *W-bosons*, both of which have spin 1. Both types of particles are very heavy, which is

why the weak interactions are so weak; roughly speaking, it takes a lot of energy to make a W or a Z. All the known quarks and leptons interact via the weak force; it is responsible, for example, for the decay of the neutron. The most obvious force is gravity, described by general relativity. Strictly speaking, gravity (and the graviton) is not part of the Standard Model. That's because particle physics is firmly based on the rules of quantum mechanics that govern the behavior of microscopic objects, but nobody quite knows how to reconcile gravity with quantum mechanics. There are good ideas in this direction, such as string theory, which we'll talk about later in the course. The graviton is spin 2.

The Higgs boson carries the final force of nature. You may previously have heard that there are four forces in nature, but I just claimed that there are five. That's because the fifth, the *Higgs force*, is part of the Standard Model but has not yet been experimentally detected. We know that something like the Higgs force has to exist because it's responsible for giving mass to all the other elementary particles, but until we've detected it, we can't be sure. If the Higgs force does exist, it's carried by a hypothetical particle called the *Higgs boson*. The search for the Higgs boson is one of the highest priorities of experimental particle physics; by the time you read this, it may already have been found! Unlike the other known bosons, the Higgs boson is predicted to have spin 0.

The dark matter particle should be neutral [or it wouldn't be dark], stable [or it would decay into something else], and slowly-moving [or it wouldn't settle into galaxies and clusters]. Within the Standard Model, all of the neutral particles are either unstable or sufficiently low-mass that they are rapidly moving—"hot" instead of "cold." Thus, there are no good dark matter candidates within the Standard Model. ■

Suggested Reading

Randall, *Warped Passages*, chapter 7.

Weinberg, *Dreams of a Final Theory*, chapter 5.

Questions to Consider

1. The Standard Model fits an impressive array of experimental tests, but its ingredients seem somewhat contrived. Can you imagine how physics would have been different with different versions of the Standard Model? What if there were four colors of quarks instead of three?

2. Draw some simple Feynman diagrams to illustrate interactions between elementary particles in the Standard Model.

3. Are you satisfied with the notion that quarks must be confined? Is it legitimate for a theory to depend on the existence of particles that can never be seen directly?

Relic Particles from the Big Bang

Lecture 9

Protons do not decay into a neutron plus a positron plus an electron neutrino because it doesn't match energy conservation. The proton is lighter than the neutron; therefore, it will never decay.

Some particles are stable—left by themselves, they will last forever—and some are unstable—they eventually decay into other particles. Most of the familiar particles (protons, electrons, and so forth) are stable as far as we know. The one exception is the neutron, which has a lifetime of about 10 minutes. The only reason that all the neutrons in the universe haven't decayed away is that they are confined inside atomic nuclei; even though a single neutron decays, it can be stable inside a nucleus.

The most important rule governing the decay of particles is that heavy particles decay into light ones but not vice versa. This is a simple matter of conservation of energy; there isn't enough energy (via $E = mc^2$) in a light particle to make a heavy one, but heavy ones can decay into lighter ones and make up the difference in the form of kinetic energy. For example, a single neutron will decay into a proton, an electron, and an electron anti-neutrino. The total mass of those three particles is less than that of a single neutron, so the decay particles must be moving at a certain speed to make the energies before and after balance. A proton, however, can't decay into a neutron plus other particles.

The most important rule governing the decay of particles is that heavy particles decay into light ones but not vice versa.

There is one other important rule: Particles carry *conserved quantities* (or *conserved charges*) that are neither created nor destroyed. The most obvious example is electric charge; the total amount of electric charge remains the same whenever a particle decays. A neutron can't decay into just a single proton, because that would violate conservation of electric charge (as well as conservation of energy). We might imagine that

the neutron could decay into a proton plus an electron, but there is a more subtle reason why that doesn't happen either.

This reason involves the conserved quantities *quark number* and *lepton number*. These are just the total number of quarks and leptons, with the important feature that antiparticles count negatively in the total. Sometimes, we define the *baryon number* to be the quark number divided by 3, because the quark number of visible particles always comes in units of 3. Both protons and neutrons have three quarks, so we say that their quark number is 3. Their lepton number is 0. But the lepton number of the electron is +1; that's why a neutron (lepton number 0) can't simply decay into a proton plus an electron. To balance out the lepton number, we must also include a particle with lepton number −1: the electron anti-neutrino. The lightest particles carrying any conserved quantity will be stable, because there is nothing they can decay into.

Consider the relationship between temperature and energy in the early universe. The early universe was a hot, dense place. Particles were close together and frequently collided. Every particle has an energy. The energy of a particle at rest is given by Einstein's famous formula $E = mc^2$. In addition, particles in motion have a different kind of energy called *kinetic energy*. These types of energy can be converted into each other, leaving the total conserved. To physicists, *temperature* measures the average kinetic energy per particle of a substance. The early universe had a high temperature—particles were moving quickly. That means that there was enough energy in particle collisions to create very massive particles that we don't normally see in the late universe. The hot, dense primordial plasma featured all manner of particles being created and destroyed. For example, a high-energy electron could collide with a proton to produce a neutron and a neutrino.

The early universe creates relic particles in predictable ways. Imagine a new kind of massive, stable particle, X, and its associated antiparticle. At high temperatures, it is constantly being created and annihilated. As the universe expands and cools, the kinetic energy per particle falls. Eventually, there isn't enough kinetic energy to create new X particles, and the remaining ones gradually annihilate away. But when the density of X particles becomes sufficiently dilute, they interact less often. If they interact sufficiently weakly,

there will be leftover particles that will last essentially forever, because they never run into their corresponding antiparticles. A classic example of this scenario involves neutrinos. They are stable and interact very rarely—only through the weak nuclear force. We think that all of space is filled with a dilute *neutrino background*, although it is very hard to detect. But the same process would also work for hypothetical dark matter particles. If there exists some particle that resembles the neutrino (stable, weakly interacting, electrically neutral) but is substantially more massive, it could very easily have the appropriate relic density to account for the dark matter today. ■

Suggested Reading

Freeman and McNamara, *In Search of Dark Matter*, chapters 11–13.

Guth, *The Inflationary Universe*, chapter 5.

Hogan, *The Little Book of the Big Bang*, chapter 6.

Weinberg, *The First Three Minutes*, chapter 4.

Questions to Consider

1. Given the particles in the Standard Model, go through each and figure out whether we should expect a considerable relic abundance or almost none. The looming unanswered question, of course, is why there is more matter today than antimatter.

2. Are the following processes allowed by the various conservation laws we discussed or not?

- A neutral pion decays into two photons.
- A neutral pion decays into two Z bosons.
- A Z boson decays into two photons.
- A W^+ boson decays into two photons.

- A W^+ boson decays into one photon and one positron.
- A muon decays into an electron and an electron anti-neutrino.
- An anti-tau lepton decays into a positron, a neutrino, and an anti-neutrino.
- A neutron decays into a proton, an electron, and a photon.
- An up quark decays into a down quark and an electron.
- A charm quark decays into an up quark and a gluon.

3. Can you imagine other ways for dark matter to be produced than the one outlined in this lecture?

Primordial Nucleosynthesis

Lecture 10

In that era, the universe was not dominated by matter and dark energy like it is today. Dark energy … has an approximately constant density as the universe expands.

What happens when we wind the movie backwards? If we follow the evolution of the universe into the past, space was smaller, and matter and radiation were more compressed; thus, the universe was both denser and hotter. The temperature of the background radiation today (about 14 billion years after the Big Bang) is about 3 *Kelvin*, corresponding to −270° Celsius, or more than 450° below 0 Fahrenheit. (1 Kelvin is the same as 1° Celsius, just with a constant offset: Absolute zero Kelvin, the lowest possible temperature, is −273° Celsius.) Temperature increases as the scale factor decreases—when the universe was half its current size, the temperature was twice as high and so on.

Let's go all the way back to about 380,000 years after the Big Bang, when the temperature was about 3,000 Kelvin (according to the Friedmann equation). At that temperature and density, atoms are knocking into other atoms with such energy that the electrons are continuously disrupted from the nuclei they are trying to attach to. At earlier times than that, when the temperature and density were even higher, there were no atoms—just free electrons and nuclei. The same kind of dissociation through energetic collisions will happen to the nuclei themselves if the temperature is high enough. Before one minute after the Big Bang, when the temperature was about 1 billion Kelvin, there were no nuclei at all—just free protons and neutrons.

Now let's wind the movie forward again. Let's begin at a time earlier than one minute and ask what happens as the universe expands and cools. At very high temperatures, the weak interactions that convert neutrons and protons into each other are actually not so weak; they happen rapidly, and the universe is a soup of interacting protons and neutrons. Because neutrons are a tiny bit heavier than protons, there aren't quite as many of them floating around.

A few seconds after the Big Bang, things cool down enough that the weak interactions essentially "turn off," allowing neutrons to decay. This decreases the number of neutrons even further. Eventually, about a minute later, things cool down enough that the remaining neutrons and protons can combine into nuclei, which they actually do quite quickly. By that time, there are about 7 protons for every neutron. One neutron can join up with 1 proton to make *deuterium*, or *heavy hydrogen*.

However, for complicated nuclear physics reasons, it's hard to make deuterium—yet easy to make helium, which is composed of 2 protons and 2 neutrons. For every 2 neutrons in the early universe, there are 14 protons floating around. These particles quickly get together to make 1 helium nucleus, leaving the other 12 protons to fly around freely. (Note that a single proton is the same as a nucleus of hydrogen.) This process is known as primordial *nucleosynthesis*. Soon after that, the density is sufficiently diluted that the combination of light nuclei into heavy ones shuts down. We are left with about 25 percent of the nucleons in helium, with the rest in hydrogen (free protons). There are also some trace amounts of other light nuclei, such as deuterium and lithium (3 protons and 4 neutrons). This story was first described by George Gamow and Ralph Alpher in 1948. They were hopeful that primordial nucleosynthesis could explain all the known elements, but that turns out not to work. These days, we understand that heavier elements arise in supernova explosions.

Nucleosynthesis is a probe of conditions during the early universe. This story of primordial nucleosynthesis predicts certain definite ratios of hydrogen, helium, deuterium, and lithium that we can compare to observations today. This comparison is complicated greatly by the fact that there is another, even more effective venue for nucleosynthesis in the later universe: nuclear fusion at the center of stars and in the supernova explosions that scatter stellar material back into the universe. That's the source of all the much heavier elements, out of which the Earth and other planets are formed. Nevertheless, we can look for pristine, star-free parts of the universe, from which we can deduce the primordial abundances.

The answers depend sensitively on different parameters of physics and cosmology. For example, if there were more than three kinds of neutrinos, the universe would be a little denser during nucleosynthesis and, therefore, would be expanding a little faster. There would be less time for neutrons to decay and, therefore, more of them to turn into helium. Cosmological observations were, in fact, the first useful constraints on the number of kinds of neutrinos. Most important, the results of nucleosynthesis depend on the total number of neutrons and protons compared to the total number of photons. The number of photons is something we can measure quite accurately today. Therefore, nucleosynthesis provides a definitive measurement of the total number of nucleons in the universe.

Nucleosynthesis provides a definitive measurement of the total number of nucleons in the universe.

Note that almost all the mass of ordinary matter comes from nucleons, because they are much heavier than electrons. The results of nucleosynthesis, therefore, provide a measurement of the total mass density of ordinary matter in the universe. The answer is: It's not nearly enough to account for the dark matter! Ordinary matter makes up only about 5 percent of the *critical density* (the density required to make the universe spatially flat), whereas the total matter density is about 30 percent of the critical density. Nucleosynthesis provides an extremely strong reason to believe that the dark matter is not just some dark kind of ordinary matter; it must be a completely new kind of particle, or it would have affected the primordial abundance of the light elements. It's amazing that we are able to extrapolate backwards from known physics to what the universe was like one minute after the Big Bang. This is an impressive testament to how well we really do understand the laws of physics. ■

Suggested Reading

Ferris, *The Whole Shebang*, chapter 4.

Hogan, *The Little Book of the Big Bang*, chapter 6.

Weinberg, *The First Three Minutes*, chapter 5.

Questions to Consider

1. Originally, cosmologists hoped to explain the origin of all the elements (not just the light ones) from primordial nucleosynthesis. Should the failure of this idea have counted against the Big Bang model?

2. How would the abundance of helium from primordial nucleosynthesis be different if general relativity were not accurate at early times and the universe had been expanding at a different rate?

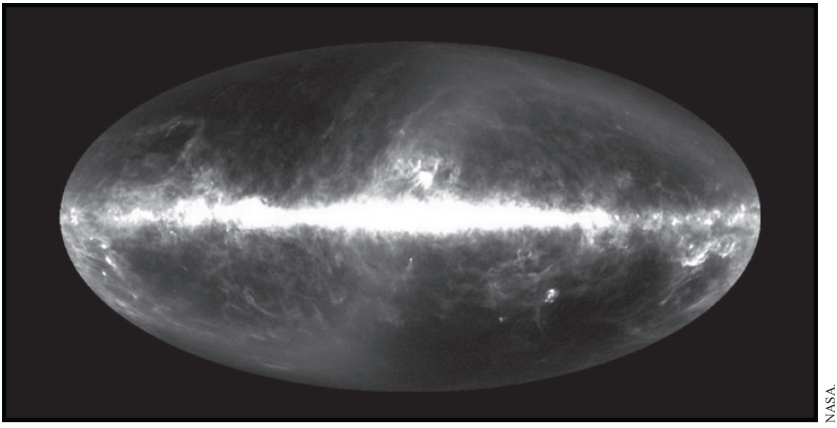
3. How would you explain to someone who hadn't listened to these lectures why cosmologists believe that the dark matter isn't just ordinary atoms that we haven't found yet?

In other words, at moments before the universe was 1/1000th of its current size, there was too much hot radiation to allow atoms to exist.

After nucleosynthesis, the universal soup of nuclei, electrons, and photons continues to expand and cool. Eventually, the temperature dips low enough that the electrons can join together with the nuclei to form atoms, a process known as *recombination*. Unlike in the case of nucleosynthesis, the byproducts of recombination don't really tell us much by themselves; they are simply photons and atoms. The real importance of recombination is that it is the moment at which the universe becomes transparent. When electrons are free, they are continually bumping into photons, which don't get very far before they are scattered. In contrast to free electrons, however, complete atoms interact with photons very rarely. Recombination is, therefore, like the lifting of a fog; suddenly, light can travel unimpeded through space, all the way to our telescopes today. When we observe this radiation, in the form of the *cosmic microwave background* (CMB), it provides us with a snapshot of what the universe looked like 380,000 years after the Big Bang. The CMB was first predicted by George Gamow, Ralph Alpher, and Robert Herman around 1950.

CMB photons fill the universe and aren't hard to detect; indeed, they contribute a small percentage of the static that appears on your TV screen. However, it is hard to separate out these microwaves from other sources of noise. The first ones to do this were Penzias and Wilson at Bell Labs. In 1965, these two researchers discovered some noise in their antennas that they could not eliminate; eventually, in talking to physicists, they realized that they had discovered the relic radiation from the Big Bang itself. Penzias and Wilson won the Nobel Prize in 1978.

CMB temperature fluctuations were first detected in 1992, and have since become an active target of observational cosmology. If the universe were precisely the same everywhere, that snapshot would be incredibly boring, but in fact, there are tiny deviations in density from place to place—the same



NASA.

Observed sky from Cosmic Microwave Background Explorer (COBE) telescope.

deviations that later grow into stars, galaxies, and clusters. The variations in density lead, in turn, to variations in temperature, which we can observe today. The CMB corresponds to a nearly uniform temperature of about 3 Kelvin, but there are small fluctuations of about 1 part in 100,000. These deviations from constant temperature are referred to as *anisotropies*, because they represent differences in how the CMB looks in different directions in the sky. If it is hard to detect the CMB, it's much harder to detect the tiny fluctuations in temperature. This was finally achieved by NASA's Cosmic Background Explorer (COBE) satellite in 1992, for which the Nobel Prize was awarded to John Mather and George Smoot in 2006. Since then, precision measurements of CMB anisotropies have become a cottage industry among astrophysicists. Instruments used include balloons, as well as ground-based radio telescopes, usually constructed in remote places far away from any interference, such as Antarctica or high in the Chilean plateau. A comprehensive, precise map of the CMB was produced by the Wilkinson Microwave Anisotropy Probe (WMAP), a NASA satellite mission that was a follow-up to COBE. Data from WMAP provide a treasure trove of information about the early universe.

Perturbations have evolved from early times into visible galaxies. We don't have any theories that predict precisely what the CMB should look like; however, our theories do predict what the typical amount of anisotropy

should be on different angular scales. That is, we can ask how much variation in temperature there is in the form of blobs that extend over different patches of the sky. Consider an overdense region in the early universe. Its tendency would be to collapse under its own gravity; however, very early on, it won't, simply because the expansion rate is too great. Once the expansion of the universe has slowed down, dense regions can begin to collapse. As these regions collapse, they heat up, and the pressure within them increases. This produces a force in the opposite direction, which causes the previously overdense region to puff up and become underdense. The process is exactly that of a sound wave and continues to oscillate back and forth. Just as sound dies out, however, so do the acoustic waves in the early universe.

When electrons are free, they are continually bumping into photons, which don't get very far before they are scattered. In contrast to free electrons, however, complete atoms interact with photons very rarely.

The story we just told plays out in different ways for regions of different sizes. If a region is sufficiently large, it never has a chance to collapse before recombination, and we see a direct imprint on the CMB. The scale at which anisotropies are the largest are those that have just had time to collapse but not to re-expand and cool off. On yet smaller scales, we see overdense or underdense regions at different phases in their evolution, depending on their size.

Dark matter plays a crucial role in the evolution of perturbations. There is one missing ingredient in the above story: dark matter. Because dark matter doesn't interact, it doesn't feel pressure, and there are no oscillations. When an overdense region initially collapses, ordinary matter and dark matter collapse together and reinforce each other. But when the ordinary matter bounces back under the influence of pressure, it goes out of phase with the collapsing dark matter, and the corresponding anisotropies are suppressed. When the same region recollapses, it's back in phase again, and the cycle repeats. Therefore, we expect to find that dark matter reinforces the anisotropy on some scales and works against it on other scales. And this is exactly what we see! The CMB provides yet more evidence in favor of dark

matter. What's more, the CMB provides a measurement of the total number of nucleons in the universe. The results agree with those of primordial nucleosynthesis. Thus, the CMB provides an independent confirmation that the dark matter cannot simply be ordinary matter in disguise; it must be some other kind of particle. ■

Suggested Reading

Goldsmith, *The Runaway Universe*, chapter 11.

Hogan, *The Little Book of the Big Bang*, chapter 5.

Kolb, *Blind Watchers of the Sky*, chapter 9.

Levin, *How the Universe Got Its Spots*, chapter 8.

Questions to Consider

1. Photons that we observe from the CMB last interacted with matter at recombination, 380,000 years after the Big Bang. Before that, the universe was opaque. In what different ways could we learn what the universe was like at times before recombination?

2. The discovery of the CMB in 1965 was counted as decisive evidence in favor of the Big Bang model. If you were skeptical about the Big Bang, how might you try to explain this phenomenon? How could you test your ideas using other kinds of observations?

3. How would the observed temperature anisotropies in the CMB change their character if there were no dark matter in the universe? What if there were much more dark matter?

Dark Stars and Black Holes

Lecture 12

So, a star will burn; the sun has been burning for about 4.5 billion years. It has about another 5 billion years worth of fuel left, but eventually will give up.

What is the dark matter? Convinced that dark matter really does exist, we should begin thinking carefully about what it might be. Although we have good evidence that it's not ordinary matter, we can still ask what direct constraints exist on hidden baryons. We'll find ourselves driven to more exotic possibilities. Could the dark matter be dark stars? Some ordinary matter is certainly "dark," in the naive sense of the term. Gas and dust, for example, may not shine in ordinary light, but they do tend to give off other kinds of light, either radio waves or X-rays. When we account for all the ordinary matter, much of it is, indeed, in the form of gas rather than of bright stars—but not nearly enough to be the dark matter.

What about dark stars? These are made in various ways. We see ordinary stars because they shine. In particular, light elements are squeezed together until they start to fuse with each other, giving off heat. But eventually, the fuel gives out. Depending on the mass, this will happen gradually or suddenly. A low-mass star will shed mass from its outer layers, and the core will shrink to a *white dwarf*. Slightly heavier stars will undergo a catastrophic collapse when their fuel runs out. Outer layers are propelled away in a (Type II) supernova explosion, while the core collapses into a *neutron star*. Neutron stars are much denser even than white dwarfs; all of their protons and electrons have combined together, leaving only neutrons behind. We can also have much lower-mass dark stars. A star can be so small that it doesn't light up in the first place; such a star is called a *brown dwarf*.

Searching for MACHOs with microlensing. White dwarfs, brown dwarfs, and neutron stars are all large, dim objects that could account for some fraction of dark matter in the haloes of galaxies. Astronomers have dubbed such hypothetical bodies *massive compact halo objects*, or MACHOs for short. We can search for MACHOs through a particular kind of gravitational

lensing known as *microlensing*. This is a type of lensing of an individual star whose gravitational field is sufficiently weak that there is no visible distortion in the image; there is, however, a slight change in the brightness of the lensed star as the lens passes by. Researchers have found such microlensing events; we can, therefore, say that MACHOs definitely exist. However, the total amount of infrared from the frequency of microlensing seems to fall short of what is needed to account for the dark matter. In addition, of course, brown dwarfs and other kinds of MACHOs are presumably made of ordinary nucleons. The strict constraints on the total amount of such particles from nucleosynthesis and the CMB rule out the possibility that these really are the dark matter.

We don't have any plausible way to make enough of these kinds of black holes to account for the dark matter.

Could the dark matter be black holes? If we squeeze enough matter into a small enough region of space, general relativity unambiguously predicts that the matter will continue to collapse all the way to a *singularity*. The gravitational field around the singularity is so strong that light itself cannot escape—a black hole. It's hard to get darker than that! Could black holes be the dark matter?

We have strong evidence that black holes do exist in the universe. They come from two basic sources: the collapse of very massive stars and the conglomeration of many such stars in the central regions of galaxies. The former type of black holes are perhaps 10 times the mass of the Sun, while the latter type are a million or more times the Sun's mass. However, this is still a tiny fraction of the mass of the entire galaxy, which is 10s of billions of times the mass of the Sun. We don't have any plausible way to make enough of these kinds of black holes to account for the dark matter. (Besides which, any conventional mechanism would make them out of nucleons, of which there aren't nearly enough, as above.) There is one loophole: There might be mysterious processes in the very early universe (before nucleosynthesis!) that produce tiny, primordial black holes. There is no observation that rules out this possibility. The strongest argument against it is simply the word *mysterious*—nobody has a good idea of how such things are made. ■

Suggested Reading

Ferris, *The Whole Shebang*, chapter 5.

Freeman and McNamara, *In Search of Dark Matter*, chapter 10.

Goldsmith, *The Runaway Universe*, chapter 6.

Nicolson, *The Dark Side of the Universe*, chapter 4.

Overbye, *Lonely Hearts of the Cosmos*, chapter 19.

Questions to Consider

1. What kinds of processes over the history of the universe could create black holes and/or dark stars?

2. Besides gravitational lensing, how might we search for such objects?

3. Imagine that we observe a set of stars orbiting a massive, unseen object. What different techniques might we use to decide whether the object is a black hole? Could we ever know for sure?

WIMPs and Supersymmetry

Lecture 13

You could also imagine that there are new particles; that there are particles that we don't see in the Standard Model yet. But, those could be the *superpartners* of the particles that we know and love.

Weakly Interacting Massive Particles are an ideal dark matter candidate. Measurements of the baryon density from nucleosynthesis and the microwave background drive us to the idea that the dark matter is a kind of particle. The only possibility in the Standard Model are the neutrinos, which are both dark (they don't interact with photons) and have a small mass. However, the details of this idea don't quite work. Although we now believe that neutrinos have mass, those masses should be very small. When neutrinos were produced in the early universe, they were *hot dark matter*—moving close to the speed of light. That's bad news for the formation of structure, because the hot dark matter tends to smooth out primordial density perturbations before they can grow into galaxies. We believe that *cold dark matter* must be dominant in the universe, which speaks against the idea that neutrinos are the culprit.

There are, thus, no good candidates for dark matter in the Standard Model. We have to invent a new kind of particle—one that is massive (cold), neutral (dark), and stable enough to last for the lifetime of the universe. One good idea is that the relevant particle interacts only through the weak nuclear force; such particles are called *weakly interacting massive particles*, or WIMPs for short. Physicists are hot on the trail of WIMPs, both experimentally and theoretically.

The hypothetical concept of supersymmetry suggests an origin for WIMPs. *Supersymmetry* is a type of symmetry that relates bosons to fermions. For every kind of boson, there will be a kind of fermion with identical properties and vice versa. As yet, this idea is completely conjectural—no evidence for supersymmetry has been found in nature. But it's a compelling idea, both theoretically and experimentally.

Naively, supersymmetry predicts that the electron, which is a fermion with charge –1, should have a bosonic partner with the same charge and the same mass. Physicists have a cute naming convention for such new particles, collectively known as *superpartners*: The superpartners of ordinary fermions get an *s* tacked on to the front, while the superpartners of ordinary bosons get *-ino* tacked onto the end. Thus, the superpartners of electrons are *selectrons*, and the partners of quarks are *squarks*; the partners of photons are *photinos* and so on.

It should be very easy to detect selectrons, but we haven't done so. Thus, if supersymmetry is real, it must be somehow hidden. That's actually not so hard to do; *symmetry breaking* is a common phenomenon in particle physics and would work to give all the new supersymmetric particles much larger masses than their ordinary partners. That means that there might be a large number of new particles to be discovered, perhaps at the next generation of particle accelerators.

It should be very easy to detect selectrons, but we haven't done so. Thus, if supersymmetry is real, it must be somehow hidden.

In order to make supersymmetry work, individual superpartners can decay into other superpartners but not exclusively into ordinary particles. This means that the lightest supersymmetric particle (LSP) is both heavy and stable—an ideal dark matter candidate! Such particles would most likely feel the weak nuclear force, which means that they are WIMPs. Indeed, supersymmetric WIMPs are the single leading candidate for the dark matter particles.

It's not enough to have these good ideas; we need to test them. A variety of experiments are currently running that would allow us to detect dark matter particles directly. *Direct detection* is the attempt to build an experiment here on Earth that is sensitive to the presence of ambient dark matter particles. In most models, dark matter particles pass through your body all the time; you just don't notice because they don't interact very strongly. But if you collect enough material and your detectors are sufficiently sensitive, you might be able to notice a dark matter particle scattering in your experiment.

Indirect detection is the idea of looking for photons created when two dark matter particles collide. If the dark matter is heavy, these photons could be very high energy, and new gamma-ray telescopes are being constructed to look for them. These telescopes will point at the centers of galaxies, where the concentration of dark matter should be especially high.

Finally, we can simply make the dark matter particles ourselves. Supersymmetry, in particular, is a major target of experiments at particle accelerators; other candidates, such as axions, require specialized detectors. It's hard to predict when we might expect definitive results from such experiments, but the next 5 to 10 years could teach us a great deal about the nature of dark matter.

Supersymmetry is the leading idea for dark matter, but it's not the only one. We could have WIMPs that arise from some other mechanism. For example, Kaluza-Klein theory imagines that we have extra curled-up dimensions of space (as in string theory, which we'll discuss later). If the size of those dimensions is just right, particles with motion in the extra dimensions would look to us as if they have extra mass, and their conserved momentum would render them stable. On the other hand, we could have cold dark matter particles that aren't WIMPs at all. For example, we could have new *sterile* neutrinos, that don't feel the weak interactions. Or we could have *axions*, hypothetical particles that are very light and created via a special mechanism. According to this hypothesis, axions arise when a certain kind of field is "frozen" in the early universe and "melts" when the expansion rate dips below a certain value. Even though they are very light, they are not moving rapidly when they are created; thus, they are cold dark matter. Axions require their own special experimental searches, which are actively underway. ■

Suggested Reading

Guth, *The Inflationary Universe*, chapter 14.

Nicolson, *The Dark Side of the Universe*, chapter 7.

Randall, *Warped Passages*, chapter 13.

Weinberg, *Dreams of a Final Theory*, chapter 5.

Questions to Consider

1. Explain why a good dark matter candidate should or should not have the following properties and which properties don't matter.

- Electrically charged or neutral.
- Strongly interacting or not.
- Stable or unstable.
- Massive or massless.
- Bosonic or fermionic.

2. Imagine that some heavy particle was produced in the early universe but decayed into some lighter (but still massive) particles after 1 million years, so that the dark matter changed its identity. Is there any way we could test this idea?

3. Is it possible that the dark matter is a complicated system of particles that interact with each other and form dark stars and planets and people?

The Accelerating Universe

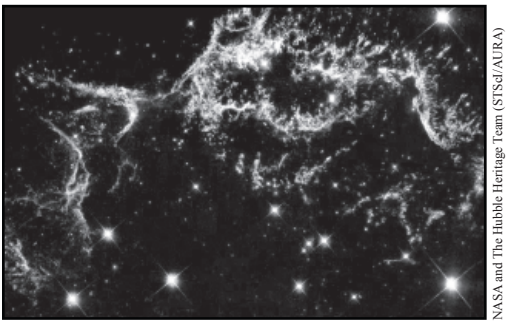
Lecture 14

The energy density is something that should be positive, like positive amounts of energy, not negative amounts of energy; that's dangerous. The Hubble constant squared doesn't matter what the value of H is. It's never going to be a negative number.

We can "weigh" the entire universe. By observing the dynamics of galaxies and clusters, we have established the need for dark matter. But how can we be sure that there isn't still more "stuff" out there in the universe, perhaps in between the galaxies and clusters? In particular, the observed matter density is only about 30 percent of the *critical density*—the density needed, according to the Friedmann equation, to accommodate a spatially flat universe. The observed value is close enough to the critical density—without equaling the critical density—that it suggests we might be missing something. (By the standards of cosmology—which spans many orders of magnitude—30 percent is very close to 100 percent.) We need to weigh the entire universe all at once. We can do this by observing how the universe expands with time. The idea is simple: As the universe expands, the matter in it exerts a mutual gravitational pull, which acts to slow the universe down. Therefore, we expect to be living in a decelerating universe. The precise rate of deceleration should tell us the total amount of matter.

Standard candles can be used to probe the expansion history of the universe. Probing the expansion history of the universe simply involves doing what Hubble did—comparing the redshifts of distant objects to their distances—but with much greater precision. For this purpose, we need standard candles that are bright enough to be visible in the very distant universe. The perfect kind of candle is provided by a certain kind of exploding star called a *Type Ia supernova*. When an ordinary star uses up all its nuclear fuel, it settles down to a white dwarf. White dwarfs cannot shrink smaller than a certain radius, simply because the electrons take up space (they are fermions, after all). But if a nearby star dumps extra matter onto the white dwarf, a point called the

Chandrasekhar limit is reached, at which gravity is so strong that the electron pressure can no longer resist. The star collapses explosively as the electrons combine with protons to make neutrons, leading to a neutron star. The outer layers of the star are blown off in the explosion, which is what we observe as a Type Ia supernova. (Other types of supernovae arise from other mechanisms.)



NASA and The Hubble Heritage Team (STScI/AURA) using data collected by Principal Astronomer Rob Fesen (Dartmouth U.) and collaborators and the Hubble Heritage team (STScI/AURA).

Supernova remnant, Cassiopeia A.

Because the Chandrasekhar limit is basically the same for every white dwarf in the universe, the brightness of the resulting explosions is basically the same, making them ideal standard candles. In fact, it's better than that—although there are small variations in the brightness, these are closely correlated with variations in the time it takes the explosion to brighten and dim again. Therefore, by observing a supernova over time, we can figure out precisely how bright the original explosion really was.

Modern techniques enable us to survey large numbers of supernovae. Supernovae are rare; only about one occurs per century in a galaxy the size of the Milky Way. Historically, that has meant that we have observed supernovae only when we've been extremely lucky. But because modern telescopes allow us to observe many hundreds of galaxies at a time, we can find supernovae almost on demand.

In the 1990s, two competing groups undertook the task of measuring the deceleration of the universe using Type Ia supernovae. One group was led by Saul Perlmutter of the Lawrence Berkeley Laboratory; one was led by Brian Schmidt of Mt. Stromolo Observatory in Australia. In 1998, they both reached the same conclusion: The universe is not decelerating at all; it's actually accelerating!

These measurements are very difficult to make, and it's natural to worry about whether they have been done correctly. Both groups were extremely careful to ensure that they understood various types of possible errors, such as obscuring dust or differences between supernovae in different types of galaxies. The fact that two competing groups reached the same conclusions gives us confidence that they know what they're doing.

Dark energy is the best explanation for the observed acceleration of the universe. How can we explain an accelerating universe? No configuration of matter, either ordinary or dark, will do the trick. We need to invent some entirely new kind of stuff—something that doesn't dilute away as the universe expands and acts as a persistent source of spacetime curvature. Further, we need something that doesn't clump into galaxies and clusters but is spread smoothly throughout space. That stuff, whatever it is, we call *dark energy*.

The bad news is that dark energy is a mystery. It wasn't really expected and continues to be hard to explain.

The good news is that dark energy completes the cosmic puzzle. If the universe is about 5 percent ordinary matter, 25 percent dark matter, and 70 percent dark energy, it fits a very wide variety of data: galactic dynamics, gravitational lensing, primordial nucleosynthesis, the cosmic microwave background, and the recent supernova surveys. It's a truly impressive model. The other good news, which helped make cosmologists accept the startling news of dark energy relatively quickly, is that dark energy helps solve a number of problems at once. It reconciles the age of the universe with that of the oldest stars and implies that the total energy density is equal to (or at least very close to) the critical density. The bad news is that dark energy is a mystery. It wasn't really expected and continues to be hard to explain. We need to work hard to confirm that it's really there and to provide better ideas for what it might be. ■

Suggested Reading

Goldsmith, *The Runaway Universe*, chapter 7.

Kirshner, *The Extravagant Universe*, chapters 6, 8–10.

Nicolson, *The Dark Side of the Universe*, chapter 9.

Questions to Consider

1. Even though the universe is "accelerating," the Hubble parameter is not increasing, as far as we know. Explain how this can be the case.

2. Given what we've learned so far and imagining that the universe continues to accelerate, describe the likely future of the universe.

3. Can you think of independent ways to test the dark energy hypothesis?

The Geometry of Space

Lecture 15

The bad news is we don't understand it. The dark energy part in particular is very exotic and outside our ordinary experience. In fact, the dark matter part is also very exotic. Ten years ago, I would be giving a set of lectures just on dark matter, and that would also seem very exciting and exotic and interesting. These days, the dark matter seems almost prosaic compared to the dark energy, which is something truly different.

Observations imply that our universe is spatially flat. In Lecture 5, we discussed how the Friedmann equation of general relativity related the expansion rate, energy density, and spatial curvature of the universe. We've now measured the total energy density (matter plus dark energy), as well as the expansion rate (the Hubble constant). If these observations are correct, there should be a testable prediction for the spatial curvature. When we run the numbers, we find an interesting answer: Given the amount of ordinary matter, dark matter, and dark energy implied by the data, space should be very close to flat (if not exactly so).

A flat universe, rather than one that is noticeably curved, has always been the favorite possibility among theoretical cosmologists. Not only is it an aesthetically pleasing middle point between positive and negative curvature, but it is a strong prediction of the inflationary universe scenario (to be discussed in Lecture 20). In addition, we have the *flatness problem*: In a matter/radiation-dominated universe, the curvature grows with respect to the energy density as the universe expands. Of course, dark energy was never a favorite possibility among theoretical cosmologists; thus, their preferences should be taken with a grain of salt.

We can measure the curvature using the cosmic microwave background. To measure the total curvature of space, we should reproduce (on a much larger scale) the kind of experiment performed by Gauss, as described in Lecture 5: Add up the interior angles of a really big triangle and see if they sum to 180 degrees. Fortunately, the universe provides us with just such a triangle.

One vertex is us here on Earth, and the other two are located on the surface of recombination, as seen in the CMB. Remember that the CMB temperature fluctuations are largest for those regions that have just had time to collapse but not to re-expand. Given that recombination happened around 380,000 years after the Big Bang, we know very well how big those regions are: They are 380,000 light years across (up to some small numerical factors that don't concern us here)! We also know how far away the CMB photons come from, giving us all the information we need about our triangle.

A flat universe, rather than one that is noticeably curved, has always been the favorite possibility among theoretical cosmologists.

In a flat universe, the largest fluctuations in the CMB should be about 1 degree across. Positive curvature would lead to a larger angular size, and negative curvature would lead to a smaller size. Observations from the Wilkinson Microwave Anisotropy Probe (WMAP) and elsewhere are perfectly clear: The primary anisotropies are, indeed, 1 degree across. Space is flat, just as the concordance cosmology dominated by dark energy says it should be.

The CMB observations of the geometry of space provide a stunning confirmation of the dark energy picture. Although it is a bold and startling idea, it (or something even more surprising) seems forced on us by the data. But dark energy is quite a puzzle. Why does it have the magnitude it does? Why is the amount of dark energy similar to the amount of matter? And, ultimately, what is dark energy? ■

Suggested Reading

Goldsmith, *The Runaway Universe*, chapter 11.

Kirshner, *The Extravagant Universe*, chapters 6, 8–10.

Lemonick, *Echo of the Big Bang*, chapter 9.

Questions to Consider

1. By observing the curvature of the universe, we claim to have measured the *total* energy density, without anything missing. Is there any way that presumption could be mistaken?

2. Besides using the CMB, can you think of any other ways to measure the universe's spatial curvature?

Smooth Tension and Acceleration

Lecture 16

The other part of dark energy is that it's persistent. The energy density in the dark energy is approximately constant as the universe expands.

Dark energy might seem mysterious and inscrutable—and it is. We don't know much about it, but we're not entirely ignorant. One thing we know is that the dark energy is persistent. It doesn't dilute away as the universe expands or, at least, not by very much. If it did (as matter and radiation do), it would have the same effect on the expansion rate of the universe as matter and radiation: It would cause deceleration.

The other important feature of dark energy is that it is smoothly distributed. For whatever reason, the dark energy does not clump into galaxies and clusters. If it did, we would have detected it through lensing and dynamics. Negative pressure is one of dark energy's characteristic features. The fact that dark energy is persistent actually implies that it has a negative pressure. That is, if you had a box with nothing but dark energy inside, it would pull the sides of the box inward rather than pushing outward as an ordinary gas would. This is less radical than it sounds; an example of negative pressure would be a series of rubber bands or springs tied to the sides of the box, pulling it inward. For this reason, negative pressure is sometimes simply called *tension*.

The relationship between persistence and tension is illustrated by the example of a piston with dark energy inside (and zero dark energy outside). Imagine, in this purely hypothetical thought experiment, pulling out on the piston as a way of mimicking the expanding universe. The persistence of dark energy means that the energy density—the amount per cubic centimeter—stays the same as the volume expands. Thus, the total amount of energy inside the piston increases; the volume goes up, while the energy per volume remains constant. That means that you have to exert a pull on the piston to move it out—you are doing work in the process. In other words, the piston is pulling back on you, just as you would expect if the stuff inside the piston had a negative pressure.

One way of thinking about why dark energy makes the universe accelerate, rather than decelerate, is to point directly to the negative pressure. According to Einstein, all forms of energy and momentum—including pressure—contribute to the deceleration of the universe. If we worked through some math (which we don't do here), we would find that the source of the deceleration of the universe is the energy density plus three times the pressure. Why three? because there are three dimensions of space. Therefore, if the pressure is sufficiently negative, the deceleration is negative (it's accelerating rather than decelerating), causing things to be pushed apart rather than pulled together. Some people like to refer to this as *antigravity*, but that's misleading; it's really just good, old ordinary gravity, with a funny kind of source. Another way of thinking about why dark energy makes the universe accelerate—without any reference to negative pressure—is to say that the universe has a persistent density, which provides a continual source for spacetime curvature. This curvature, in turn, keeps the universe expanding.

What the Hubble parameter is telling you is how long it takes for the universe to increase in size by some fixed number.

Why does a persistent source of energy density make the universe accelerate? Let's return to the claim that persistent energy density makes the universe accelerate. In general relativity, the expansion of the universe is driven by the energy density. If the spatial curvature of the universe is zero, as data from the cosmic microwave background suggest, then the energy density is proportional to the expansion rate squared. That expansion rate is measured by the Hubble constant—by the Hubble parameter that relates the velocity that you observe in the galaxy to the distance that it is from you. Therefore, a nearly constant density should lead to a nearly constant Hubble parameter. Why should a constant expansion rate be described as "accelerating"?

The point is that the expansion rate of the universe is not a velocity; it's the rate at which the universe increases in size by some multiplicative factor. For example, imagine that the Hubble parameter takes some constant value such that the universe doubles in size every 10 billion years. If we have two galaxies that are 10 million light years apart, then 10 billion years later, they

will be 20 million light years apart. But in another 10 billion years, they will be 40 million light years apart, and 10 billion years after that, they will be 80 billion light years apart! Thus, a constant Hubble parameter means that the rate at which two galaxies move apart is actually getting faster and faster.

We can say the same thing in another way: Hubble's law says that the apparent velocity of a distant object is given by Hubble's constant times the distance—what the Hubble parameter is telling you is how long it takes for the universe to increase in size by some fixed number. Now imagine that Hubble's parameter is truly constant. With the current value of the Hubble constant, the universe would double in size roughly every 10 billion years. For any given object, the distance is increasing as the universe expands; therefore, we would observe the recession velocity to be increasing, which is the definition of *acceleration*. The only reason we expect deceleration in a conventional, matter-dominated universe is that the Hubble "constant" decreases sufficiently fast that the velocities decrease, as well. ■

Suggested Reading

Goldsmith, *The Runaway Universe*, chapter 5.

Guth, *The Inflationary Universe*, appendix A.

Livio, *The Accelerating Universe*, chapter 5.

Questions to Consider

1. Think of some everyday objects that have a negative pressure. What will their gravitational fields be like?

2. What would happen if the density of dark energy were increasing with time? How would we know?

3. Let your imagination roam free of the constraints of conventional technology and engineering (but not the laws of physics). Is there any way you could imagine to use dark energy as a source of energy here on Earth?

Vacuum Energy

Lecture 17

The two things we know about dark energy are that it's smoothly distributed through space and nearly constant in time; therefore, certainly the simplest thing it could possibly be is something that is absolutely 100 percent the same from place to place in space and the same from moment to moment in time.

The simplest possible kind of dark energy is vacuum energy. We know that the dark energy is fairly smoothly distributed and fairly persistent in density. The simplest possibility, therefore, is that it is exactly constant in density, both across space and through time. This possibility is called *vacuum energy*, or the *cosmological constant*. The concept of vacuum energy is not exactly the same as that of dark energy; the former is a specific candidate for what the latter might be. (In other words, the vacuum energy might be exactly zero, and the observed dark energy might be something else, as we'll discuss in the next lecture.) Vacuum energy is simply the energy inherent in space itself. Consider a tiny region of space that is perfectly empty: no matter, no radiation, nothing at all. Then ask, "How much energy is contained in this region?" You might think that the answer is necessarily zero, but that's not right; according to general relativity, the answer is a constant of nature—the energy of empty space.

Einstein thought of the cosmological constant as his greatest blunder. Soon after Einstein invented general relativity, he applied it to the entire universe. He found that such a universe must be either expanding or contracting—there was no static solution, because the matter in the universe would be pulling on all the other matter. But astronomers of the time (before Hubble came along) assured him that the real universe was, in fact, static.

Einstein could have stuck to his guns and made the bold prediction that the universe must be either expanding or contracting. But instead, he invented the concept of vacuum energy, which he called the cosmological constant. He invented a model of the universe in which the accelerating impulse of the cosmological constant precisely balanced the decelerating impulse of

the matter (with some spatial curvature added to make the math work out correctly). This was not Einstein's best idea, because the resulting model wasn't really stable; any tiny perturbation away from perfect balance would make the universe either expand or collapse. When Hubble reported that the universe was actually expanding, Einstein realized that he had made a mistake and reportedly referred to the cosmological constant as his "greatest blunder." However, Pandora's box is not so easily closed; once the concept of an energy density inherent in empty space is introduced, it becomes hard to ignore.

Einstein thought of the cosmological constant as his greatest blunder.

Vacuum fluctuations contribute to the value of the cosmological constant. The modern picture of the vacuum relies heavily on the precepts of quantum mechanics. In particular, we have Heisenberg's uncertainty principle, which says that it is impossible to pin any system into one particular well-defined state. For example, we can't guarantee that a pendulum is sitting at the bottom of its arc, even if we know that it's in the lowest-energy state. There is always some irreducible quantum jitter. Usually, we apply the uncertainty principle to an elementary particle, such as the electron, but it also applies to empty space. In that context, it means that it's impossible to make space perfectly empty—even in the emptiest state, there will be *virtual particles* that constantly pop in and out of existence. The existence of virtual particles is not in doubt—not only are they predicted by quantum mechanics, but their effects have been observed, for example, in the energy levels of atoms. But remember, everything couples to gravity, and that includes virtual particles. The energy of these particles contributes to the vacuum energy (as do other things).

We can't precisely calculate the predicted vacuum energy from quantum fluctuations, but we can roughly estimate its likely value. Our best estimates, unfortunately, give an answer (10^{112} ergs per cubic centimeter) that is much larger than the observed density of dark energy (10^{-8} ergs per cubic centimeter) by a factor of 10^{120}. That's 1 followed by 120 zeros, an absurdly large number. (For comparison, there are only about 10^{90} particles in the entire observable universe.) This is known as the *cosmological constant problem*, and nobody knows how to solve it.

The cosmological constant problem was known long before dark energy was discovered. In those days, however, there was a plausible loophole: Some unknown symmetry or other law of physics might be setting the vacuum energy to zero for reasons that we would someday discover. If the observed dark energy is, in fact, vacuum energy, those hopes have been dashed. This makes the problem worse rather than better; it's one thing to imagine an unknown mechanism that completely cancels some number and sets it to zero, but it's much harder to imagine a mechanism that makes the number much smaller than it should be but not quite zero. So in the next lecture we'll consider an alternative scenario: Perhaps the vacuum energy is zero after all and the dark energy we're seeing is, not a cosmological constant of the vacuum, but instead something dynamical. ■

Suggested Reading

Cole, *The Hole in the Universe*, chapter 4.

Livio, *The Accelerating Universe*, chapter 5.

Vilenkin, *Many Worlds in One*, chapter 2.

Questions to Consider

1. Put yourself in Einstein's shoes after he had invented general relativity but before Hubble had discovered the expansion of the universe. Should Einstein have been able to predict that the universe would be expanding or contracting? Was the cosmological constant really a great blunder?

2. Can empty space really have energy? Would there be any way to create a region of space with even less energy than the vacuum energy?

3. Given that the cosmological constant is much smaller than it should be, do you think it was a sensible expectation for physicists to have guessed that it was exactly zero, even if they didn't know why?

Quintessence

Lecture 18

If the cosmic strings have the property that when two strings bump into each other they get tangled, the total energy density in cosmic strings can evolve very slowly, if at all.

Dark energy could be dynamical, rather than strictly constant. One motivation for considering dynamical dark energy is the cosmological constant problem: It is still easier to imagine setting the vacuum energy precisely to zero, even if we don't know how to do it, and then adding a new field to bring the observed dark energy up to its current value. We know from observations that the density of dark energy is nearly constant through space and time. Vacuum energy is the idea that it is precisely constant; however, we can also consider the possibility that there are mild variations in the density. The simplest way to get such variations is to imagine that the dark energy is generated by some dynamical field, called *quintessence*. This would be a new bosonic field in nature, somewhat similar to the electromagnetic field, but with the crucial difference that its energy density remains nearly constant as the universe expands. It's not difficult to invent explicit particle physics models of such fields if one is allowed arbitrary freedom to tune the relevant parameters in the theory to the appropriate values. If a quantum field is like an infinite collection of swinging pendulums, the quintessence pendulums are moving in cold molasses, taking billions of years to reach the bottom of their arcs.

Another motivation is the *coincidence scandal*: Why are the densities of matter and dark energy so similar? The important fact here is that the two quantities evolve rapidly with respect to each other as the universe expands: The matter density dilutes away, while vacuum energy remains constant. If they are similar today, they were very different in the past (matter was dominant) and will be very different in the future (vacuum energy will be dominant). Replacing a constant vacuum energy by a dynamical field allows us to contemplate some dynamical solution to this problem. Once again, no promising solution along these lines is known, but at least we can contemplate it.

Quintessence comes in a variety of forms (all completely hypothetical, of course). If the density is gradually decreasing, the universe can be accelerating, but the Hubble parameter will nevertheless gradually diminish. We can also, more dramatically, imagine that the dark energy density is actually increasing; this possibility is called *phantom energy*. In that case, the Hubble parameter will increase. And if it increases quickly enough, we can have a *Big Rip*—a future state of super-fast expansion that pulls everything in the universe to bits. There are good theoretical reasons to doubt the existence of phantom energy, but it is (as usual in this game) good to keep an open mind.

To test the evolution of the energy density, we probe the behavior of the scale factor as a function of time.

Another thing to keep in mind is that, when going from a single number (the vacuum energy) to an entire dynamical field (quintessence), we open the possibility of directly detecting the dark energy, just as we hope to directly detect the dark matter. That is, we can imagine that quintessence couples directly (although weakly) to ordinary matter. One effect of such a coupling would be a new force that stretched over macroscopic distances—a so-called *fifth force* (because the Higgs force is usually not counted). Experiments are currently underway to look for precisely such kinds of forces. It's good to keep in mind that, although so far our only evidence for dark matter and dark energy has been through gravity, we may someday be able to detect them in much more direct ways.

Quintessence has another virtue: It's observationally testable. Dark energy makes the universe accelerate because it has a persistent (nearly constant) energy density. But if the density is slowly varying, the rate of acceleration will be subtly different from the case where the density is truly constant, and that difference is, in principle, observable. The possibility that the dark energy density evolves with time is usually couched in terms of an *equation-of-state parameter*, often denoted w. This is the number that relates the pressure to the energy density. If the density is strictly constant, w is exactly -1, because the pressure is exactly the opposite of the energy density. If the density is slowly decreasing, w is slightly greater than -1 (that is, -0.9 or something like that); if the density is slowly increasing, w is slightly less

than –1. This isn't an especially helpful way to think about things, but it's conventional among working cosmologists.

To test the evolution of the energy density, we probe the behavior of the scale factor as a function of time. In other words, we do something like the supernova projects did, although to much better accuracy. A variety of new observational programs—using supernovae, lensing, and other cosmological probes—are now underway to do exactly this. ■

Suggested Reading

Cole, *The Hole in the Universe*, chapter 8.

Nicolson, *The Dark Side of the Universe*, chapter 11.

Vilenkin, *Many Worlds in One*, chapter 14.

Questions to Consider

1. The idea that the dark energy is a strictly constant vacuum energy, or cosmological constant, seems to fit all the data we have. Is there a good motivation for continuing to think of alternative models for what the dark energy might be?

2. Phantom energy could lead to a Big Rip in the future, but it's hard to know for sure. What would we need to be able to say with confidence in order to predict that certain things will happen in the distant future of the universe?

3. Can you think of different ways to measure the equation-of-state parameter of the dark energy? What about its value at earlier times in the history of the universe?

Was Einstein Right?

Lecture 19

I should say that Einstein, of course, is a famous physicist and he's a very smart guy. But, even though his theory is very good, there is nothing sacred about it; therefore, there is nothing sacrilegious about questioning general relativity. There is a feeling that some people have, that we establishment cosmologists have, as our duty, to defend Einstein's honor against attacks from talented but quirky outsiders. Nothing could be further from the truth.

We believe in the dark sector because we infer its existence, not because we detect it directly. As we have emphasized, there is considerable observational evidence in favor of dark matter and dark energy. However, all that evidence proceeds in a very specific way: We measure gravitational fields (the curvature of spacetime), deduce what kinds of sources are necessary to produce such fields, and find that ordinary matter is insufficient. The deduction necessarily involves our understanding of gravity in the form of Einstein's equation of general relativity. But what if general relativity is not right? More specifically, what if it is an excellent approximation to reality in the Solar System (where we have tested it to very high precision, and it passes with flying colors) but increasingly deviates from the right answer on the larger length scales characteristic of cosmology?

It's worth emphasizing that there's nothing sacrilegious about contemplating alternatives to Einstein's theory. General relativity is a cornerstone of modern physics, but nobody believes that it is absolutely the last word on gravity. If nothing else, general relativity is expected to break down on very small scales, when quantum gravity becomes important (as we'll consider in Lecture 21). It's perfectly acceptable—if something of a long shot—to wonder whether it might break down on very large scales, as well.

Planets in the Solar System provide an ambiguous historical lesson. In the 19th century, French mathematician Urbain LeVerrier suggested the existence of an undiscovered celestial body—the dark matter of its day—to help explain the orbit of Uranus. Sure enough, in 1846, astronomers discovered

the planet Neptune. Encouraged, LeVerrier tried again, proposing a new inner planet to help explain the discrepant orbit of Mercury. But this planet, labeled Vulcan, was never found; as we now know, Mercury's orbit is explained by improving our theory of gravity from Newton's inverse-square law to Einstein's general relativity.

Compared to dark matter, we know rather little about dark energy.

We can ask the question separately for dark matter and dark energy. Evidence for dark matter comes from the dynamics of galaxies and clusters; generally, there is a stronger attractive force due to gravity than we would ordinarily expect. Dark energy, meanwhile, is deduced from the global behavior of the universe: the accelerated expansion and the flat geometry of space. Dark energy, in contrast to dark matter, appears to be repulsive, causing galaxies to accelerate away from each other. The best possible theory of modified gravity, of course, would account for dark matter and dark energy in one fell swoop; it would, nevertheless, still be interesting to do away with one of them, even if we had to keep the other.

Doing away with dark matter is a difficult proposition. he most celebrated attempt to replace dark matter with modified gravity is credited to Mordehai (Moti) Milgrom, who invented a theory called *modified Newtonian dynamics* (MOND). Milgrom looked at the rotation curves of spiral galaxies and noticed something interesting. In the central regions, no dark matter was needed; the visible matter was able to account for the observed dynamics. Dark matter was only necessary past a certain point, which is to be expected. The unexpected thing was that, for all sorts of different galaxies, the acceleration due to gravity at the point where dark matter became important was the same. Milgrom suggested that this was not an accident, that there is no such thing as dark matter, but instead, that the character of gravity (how fast the gravitational force falls off with distance) changes when the acceleration becomes very low.

One big strike against Milgrom's theory was that it was incomplete. General relativity makes specific predictions for galaxies but also for many other phenomena—the Solar System, lensing, gravitational waves, and cosmology, just to name a few. MOND didn't, for a long time, have anything to say

about such things. However, in 2004, Jacob Bekenstein finally invented a theory that could answer all these kinds of issues; in fact, it did pretty well in confronting the data.

The real problem for MOND in its current form comes from clusters of galaxies. Clusters are often in the regime where the MOND rules should apply, but they don't seem to fit what is observed. Even MOND's boosters now concede that there is only one way to make the theory fit the cluster data: dark matter! The idea is that you could have hot dark matter, such as neutrinos, in the clusters; the hot particles would stream out of galaxies, which are explained by modified gravity, but remain stuck in clusters. This idea is currently compatible with the data, but it doesn't really add up to a compelling picture.

Doing away with dark energy is more plausible, although that still faces difficulties. Compared to dark matter, we know rather little about dark energy. At a certain point, late in the universe's history, it begins to accelerate at a certain rate—we don't know much more than that. There is correspondingly more room to try to invent a theory of modified gravity that can fit the data even without dark energy. However, modifying gravity turns out to be very difficult in practice. It's easy (as these things go) to modify gravity to make the universe accelerate; however, it's very difficult to invent such a theory that remains compatible with what we know of gravity from other experiments.

Nevertheless, we plunge forward. The good news is that the acceleration of the universe isn't the only cosmological manifestation of gravity; there is also the evolution of structure, from small ripples in the CMB to galaxies and clusters. Modifying gravity to make the universe accelerate will generically alter the predicted pattern of structure evolution. The next generation of observations, therefore, will place special emphasis on comparing the implications of the expansion history of the universe to the history of structure growth. ■

Suggested Reading

The ideas discussed in this lecture are sufficiently speculative and new that no good book discusses them in any detail. For some general ideas about gravity and how it might be modified, see the following references.

Greene, *The Fabric of the Cosmos*, chapters 13–14.

Randall, *Warped Passages*, chapters 18–22.

Will, *Was Einstein Right?*

Questions to Consider

1. Einstein was a smart guy, and his general theory of relativity has already passed a great number of observational tests. Does it make sense to keep inventing new theories rather than stick with the one that works?

2. Do you think we'll ever be able to know for sure whether there is dark energy or, instead, whether gravity is modified? Likewise for dark matter?

Inflation

Lecture 20

Inflation, of course, is also similar to dark energy, physically. We have some field that is making the universe accelerate, some energy density that doesn't go away very quickly. That's what you need for dark energy. That's also, separately, what you need for inflation, so by thinking about one, you might better understand the other.

Despite the successes of the Big Bang model, it raises some nagging problems. These are not direct problems with fitting data but problems of naturalness—why is the universe arranged in some particular way that seems rather unlikely to us? The horizon problem is the most puzzling feature of the conventional Big Bang scenario. When we observe widely separated parts of the CMB sky, they are at approximately the same temperature; the universe, as we've stressed, is very smooth on large scales. But we're observing those two points as they were far in the past, because light travels from there to here at a finite speed. And at those times, the universe was much younger—about 380,000 years old. This is problematic, because the physical distance separating those two points at that time was much larger than 380,000 light years! Thus, we're observing two regions that were never in *causal contact*—no signal could possibly have propagated from one region to the other. If they were *never* in contact with each other, the question is, then: how did they possibly "know" that they were supposed to have the same temperature?

The flatness problem is a bit more subtle, and experts argue over its importance. Consider a universe with only matter and radiation, no dark energy. If there is any nonzero spatial curvature in such a universe, its effects will tend to increase in importance as the universe expands. Thus, we might expect, late in the universe's history, for curvature to be important. But the real world is spatially flat as far as we can tell. Why is that?

The inflationary universe scenario uses accelerated expansion in the early universe to resolve the puzzles of conventional cosmology. In 1981, Alan Guth realized that both the horizon and flatness problems could be

simultaneously solved by a simple mechanism: a brief period of accelerated expansion in the very early universe, which he dubbed *inflation*. If the early universe was not dominated by matter and radiation but by some form of (what we would now call) ultra-high-scale dark energy, it would undergo acceleration at a fantastic rate. This would tend to blow up a tiny patch of space to a fantastically large size, smoothing and flattening it out all the while. In this way, both the horizon and flatness problems would be solved at once. Inflation quickly became a popular idea, although it was faced with a significant empirical challenge: At the time, observations did not indicate that space was flat! When people measured the amount of matter in the universe, it fell short of the amount required.

Because inflation happens at a nearly constant rate, it predicts that the perturbations in density should be nearly the same at every length scale.

The discovery of dark energy has provided a great boost to the inflationary universe scenario, for two reasons. First, it demonstrated unambiguously that it was possible for the universe to accelerate, which had not previously been obvious. Second, it accounted for the extra energy density required to make the universe perfectly flat. Thus, a prediction of inflation came true. The mechanism behind inflation—a brief period of accelerated expansion driven by an approximately constant energy density—sounds very similar to the idea of quintessence in the contemporary universe. It's natural to wonder whether they might be connected; right now, the answer is far from clear. The biggest obstacle to a unification of the two ideas is the tremendous separation between them in just about any measure: time, density, energy, temperature—you name it. Furthermore, in between inflation and the present day, we have good evidence from nucleosynthesis and the CMB that the expansion of the universe was dominated by matter and radiation in the conventional way. It seems plausible that inflation and dark energy are completely separate phenomena, but we can't yet be sure.

The idea of inflation came with an unexpected bonus—a simple mechanism for generating the primordial density perturbations that grow into large-scale structure. Inflation does its best to smooth out the universe. However, as we've mentioned, Heisenberg's uncertainty principle prevents any state from

being perfectly well defined, including the whole universe. Therefore, there is a certain minimum uncertainty in the geometry of space as it expands during inflation; this uncertainty translates directly into a set of perturbations in the energy density.

Because inflation happens at a nearly constant rate, it predicts that the perturbations in density should be nearly the same at every length scale. That prediction can be tested precisely against the data; so far, the universe seems to be in good accord with what inflation predicts. It is truly a mind-bending suggestion—that the huge and majestic galaxies we see throughout the universe trace their origins back to quantum fluctuations at literally subatomic scales. ■

Suggested Reading

Greene, *The Fabric of the Cosmos*, chapter 10.

Guth, *The Inflationary Universe*, chapters 10–12.

Overbye, *Lonely Hearts of the Cosmos*, chapters 13–14.

Vilenkin, *Many Worlds in One*, chapter 5.

Questions to Consider

1. The horizon and flatness problems deal with the initial conditions for our whole observable universe. We are, of course, stuck with the universe that we have. Should the nature of the initial conditions count as a scientific question?

2. The ideas of inflation and quintessence are very similar in spirit. Do you think they might be connected? What arguments could you put forward in favor of or against such a possibility?

3. Can we ever know for sure whether inflation happened in the early universe?

Strings and Extra Dimensions

Lecture 21

We don't know what the strings are made of. It's not even a sensible question to ask. They are made of the stuff that strings are made of. But, the idea is the different ways you can vibrate a string correspond to all the different particles that we see.

Quantum mechanics and gravity will ultimately need to be reconciled. As a matter of practice, the Standard Model combined with general relativity does a wonderful job of accounting for essentially all our experimental knowledge about how the universe works, at least here on Earth. But as a matter of principle, these two frameworks are fundamentally incompatible. Particle physics operates within the framework of quantum mechanics, while general relativity has stubbornly resisted incorporation into that picture. Reconciling general relativity and quantum mechanics is perhaps the single most important problem in fundamental physics today.

There are conceptual obstacles to coming up with a working theory of quantum gravity, but there are also direct technical problems. Consider the scattering of two particles interacting via gravity. If we draw the simplest Feynman diagram describing such a process, it gives a sensible answer, which should be a good approximation to the exact answer. To improve the approximation, we start including somewhat more complicated diagrams. When we calculate the contributions corresponding to these diagrams, however, we find that they are infinitely big! This result is not at all a small improvement to a sensible answer. Sometimes, in the course of doing quantum calculations, we find infinite answers that aren't that worrisome—they can be "renormalized" into finite answers. For quantum gravity, that doesn't seem to be the case; the answers simply don't make sense.

String theory is the leading candidate for a consistent theory of quantum gravity. String theory has a daunting reputation, but at heart, it's an extremely simple idea. In ordinary particle physics, we imagine that every particle is a perfect mathematical point. If you were to zoom in ever closer with a microscope, it would remain perfectly pointlike. String theory simply

says that this process actually does not continue forever. If you look closely enough (much more closely than we currently have the ability to do), particles resolve themselves into tiny loops of string. These strings are approximately the Planck length (roughly 10^{-33} centimeters); that's much smaller than the size of a proton (about 10^{-13} centimeters). You can't ask what the strings are made of—they're made of string stuff; that's as deep as it goes. But from that one simple idea, many consequences flow.

Whereas ordinary field theories seem to be incompatible with gravity, string theory necessarily predicts it!

One consequence is gravity. Whereas ordinary field theories seem to be incompatible with gravity, string theory necessarily predicts it! One of the vibrational modes of a string, like it or not, is a spin 2 massless boson with all the couplings of a graviton. Furthermore, the extended nature of the string works to smooth out the infinities that are so troublesome in naive approaches to quantum gravity. Not only is string theory a quantum theory of gravity, but it's a well-behaved (finite) one. The bad news is, as attractive as string theory is in principle, it's extremely hard to connect it to practice, for reasons we'll see in a moment.

Extra dimensions are a prediction of string theory. How do we know that three dimensions of space (and one of time, of course) are all there are? One way is to tie sticks together; you can tie three sticks together so that each one is perpendicular to the other two, but you can't do the same trick with four. However, in the dynamical spacetime of general relativity, we can imagine that there are actually extra dimensions of space but that they are curled up into tiny spaces too small for us to notice. Indeed, this idea was pursued by Theodor Kaluza and Oskar Klein soon after general relativity was first invented. Extra dimensions remained an amusing possibility for a long time. But the emergence of string theory brought them back with a vengeance, for a simple reason: Although extra dimensions are optional in GR, in string theory, they are mandatory.

Strings require the existence of extra dimensions; to make the idea compatible with our observed world, they must somehow be hidden. The simplest way is to follow Kaluza and Klein and simply curl them up into an

invisibly tiny space. But string theory is not just a theory of strings; it also predicts larger objects extended in one or more dimensions—objects known as *branes* (derived from the word *membrane*). Imagine a brane with three spatial dimensions, embedded in a larger space of more dimensions. An interesting feature of branes in string theory is that certain types of strings (and, thus, certain types of particles, from our macroscopic point of view) can be confined to the brane. We can imagine, in fact, that all the particles of the Standard Model that we know and love are actually confined to a three-dimensional brane in some larger universe. In such a scenario, we don't notice the extra dimensions simply because we can't get there—we're made of such particles ourselves, after all.

The upshot of this story is that there are many more ways to hide the extra dimensions than we previously suspected. We don't know exactly how many, but such numbers as 10^{500} are routinely suggested. Every one of these ways gives rise to a macroscopic world with a different set of particles and forces. Just as water can come in different phases—solid, liquid, and gas—so can spacetime itself, according to string theory. Except that, instead of three phases, there are 10^{500}. All these different phases, unfortunately, represent a significant obstacle in our attempts to tie string theory to the real world. We should live in one of these phases, but which one? Gravity is a very weak force, which makes it difficult to devise direct experimental probes of any theory of quantum gravity; we hope that we will eventually be clever enough to think of a way to test the theory experimentally. ■

Suggested Reading

Greene, *The Fabric of the Cosmos*, chapters 12–14.

Randall, *Warped Passages*, chapters 14–16.

Questions to Consider

1. It's hard to think of ways to test string theory experimentally. On the other hand, both gravity and quantum mechanics are part of physics and should eventually be reconciled. How far can physics go on the basis of thought experiments alone?

2. Imagine that we did find experimental evidence in favor of string theory and derived a unique model connecting it to the real world. Would that be the end of physics?

3. Critics of string theory have suggested that it has occupied the efforts of too many bright young physicists, who find it difficult to strike out with their own radical new ideas. How can we balance work on a promising but speculative approach with attempts to try something completely different?

Beyond the Observable Universe

Lecture 22

Just as water can come in different phases of liquid water, solid water of ice, and water vapor, it's the same underlying thing. It's not like there are three different theories—a theory of water vapor, a theory of ice, and a theory of liquid water; it's the same stuff manifesting itself in different forms. Likewise, what string theory is saying is that there are perhaps 10^{500} different phases of spacetime—all of these different ways in which the fundamental vibrational modes of the string can show up as particles, as numbers of particles, and as the vacuum energy.

Cosmological horizons set a limit on what we can observe. We can't see the whole universe. There is only a finite amount of time between us and the Big Bang, which constitutes a barrier past which we can't possibly observe anything. Light, meanwhile, travels at a finite speed and, therefore, reaches back only so far before (in principle) it runs into the Big Bang. The boundary defined by the furthest point from which light can reach us is known as our *horizon*.

The universe we can observe is homogeneous—pretty much the same everywhere. Is that still true beyond the horizon, potentially out to infinity? Maybe or maybe not. We have no way of ever knowing via observation; the best we can do is to contemplate different theoretical possibilities.

The idea that there are many regions of space with different physical properties is known as the "multiverse." String theory and other models with extra dimensions suggest that our macroscopic four-dimensional spacetime can find itself in any one of a large number of possible states. In each of these states, the local "laws of physics" will appear to be different—the number of particles; their masses, spins, and charges; perhaps even the number of dimensions. Inflation, meanwhile, provides a potential mechanism for turning these possible states into actual states—all at the same time but in widely separated regions of the universe. Inflation takes microscopically small patches of universe and expands them into cosmologically huge regions. It's perfectly plausible that inflation creates pockets of space in every one of the

possible states suggested by string theory. In other words, we could live in one homogeneous subset of an enormously vast multiverse. We have no way of knowing for sure, but it's a plausible scenario.

Environmental selection is a possible explanation for the observed value of the cosmological constant. "Why should I care?" is a perfectly rational response to speculations of this sort. All those other parts of the multiverse are beyond any possible observation—why should their status affect how we think in any way? The answer—which may or may not be right or sensible—is that the existence of such a multiverse can change what we think of as "natural." We've already mentioned that the vacuum energy is extremely small, at least compared to its natural value. But here's the rub: If the vacuum energy actually had its natural value, we wouldn't be here to notice. Life could not exist if the cosmological constant were very large. If it were large and positive, it would accelerate the universe so fast that atoms and other structures couldn't form. If it were large and negative, the universe would recollapse in a microscopically short period of time. Even though the observed vacuum energy seems unnatural, in a sense, it couldn't be very different; if it were, we wouldn't be measuring it.

Life could not exist if the cosmological constant were very large. If it were large and positive, it would accelerate the universe so fast that atoms and other structures couldn't form.

Thus, the concept of a multiverse leads us to think in terms of *environmental selection*: In a collection of many different environments, we will only ever observe those that are compatible with our existence. If such an ensemble really does exist, it shouldn't be at all surprising that the vacuum energy is small. We could imagine asking, right here in our Solar System, why we were so lucky to have life arise on the hospitable Earth rather than the overheated surface of the Sun, which after all, is much larger. But of course, it's not luck at all; life can't arise on the surface of the Sun, so that was never an option.

What does this mean for dark matter and dark energy? For dark matter, not much: The existence of dark matter doesn't seem to be crucial for our way of life. But dark energy is a different story. If the dark energy were large and positive, the acceleration would be so rapid that atoms couldn't form, much less galaxies. And if it were large and negative, the universe would recollapse in a fraction of a second. Even though the observed magnitude of the dark energy seems unnatural to us, it had to be close to the current value for us to be here in the first place. If, indeed, we live in a multiverse, it's not surprising that we live in a part of it that is hospitable to us being here.

Such reasoning often goes under the name of the *anthropic principle*. Many people object to this principle on philosophical grounds, especially because the existence of the multiverse is impossible to verify (or disprove). It's important to realize, however, that the multiverse is not by itself a scientific theory; it is, at best, one component of a larger theory. The ultimate test is whether or not that theory (which is, at present, completely hypothetical in its own right but should, eventually, include string theory, as well as inflation) makes other predictions that are testable against experiment. If not, it can't really qualify as science. ■

Suggested Reading

Livio, *The Accelerating Universe*, chapters 9–10.

Randall, *Warped Passages*, chapters 19–20.

Vilenkin, *Many Worlds in One*, chapters 10–15.

Questions to Consider

1. Should physics ever address parts of the universe we can never observe? Does this count as "science" in your estimation?

2. Imagine that researchers managed to use environmental/anthropic reasoning to make an explicit prediction about particle physics, which was later verified at the Large Hadron Collider. Would that count as evidence in favor of this approach?

3. We don't know what forms intelligent life could possibly take in different physical conditions (or even in the conditions we observe). What do you think are the minimal requirements for the laws of physics and conditions in the universe to support life?

Future Experiments

Lecture 23

Only very recently have we been able to develop cameras that can take images of what's in the sky to such precision that you can tease out the slight perturbations of the shapes of galaxies due to gravitational lensing.

We have a model that fits the data extremely well. The current best-fit model of the universe invokes a number of amazing ideas, such as dark matter, dark energy, and density fluctuations that may be generated by a period of inflation in the very early universe. Nevertheless, the model fits an impressively diverse collection of data. So far, nothing we see about the universe is in substantial conflict with this standard cosmological model. However, we want to do better. We're not content to *describe* the universe; we want to *understand* it. To that end, of course, we need better theoretical ideas, and the easiest way to hit on those ideas is to have new experimental input.

With this technology, plans are on the drawing board to dramatically improve a number of different kinds of cosmological observations.

There are many ways to look at the universe with photons. Since ancient times, we've gathered information about the heavens by looking with our eyes, suitably aided by technology. In this day and age, we can detect photons across the electromagnetic spectrum, from long-wavelength radio waves to short-wavelength X-rays and gamma-rays. With this technology, plans are on the drawing board to dramatically improve a number of different kinds of cosmological observations. Such efforts include the following:

- Deeper probes into what we can learn from the cosmic microwave background, e.g., comparing the fluctuations at large angles in the sky to fluctuations at smaller angles in order to measure the amounts of (and fluctuations in) dark energy, dark matter, and ordinary matter in the early universe.

- Surveys of galaxies and large-scale structure, e.g., the Sloan Digital Sky Survey (Arizona) and the Two-degree Field Survey (Australia).

- Maps of gravitational lensing to infer the location of dark matter and the evolution of structure.

- Detailed examination of clusters of galaxies, because the number of clusters of galaxies in the universe at different distances (at different redshifts) is a very promising way of figuring out how much dark energy there is.

- More measurements of Type Ia supernovae at large distances in order to figure out whether the dark energy is truly constant or slowly varying.

- Gamma-ray satellites to look for annihilating dark matter, e.g., GLAST (Gamma-ray Large Area Space Telescope).

Increasingly, we can also use particles besides photons. It's only relatively recently that technology has developed to the point where we are not limited to using only electromagnetic radiation to probe the universe. Current and upcoming observations will use:

- Cosmic rays, which are high-energy protons and nuclei from cosmological distances.

- Neutrinos; those currently measured are only from the Sun, but we're looking for other sources.

- Gravitational waves; they have not yet been directly detected, but more advanced observatories have recently become operational.

    - In 2007, LIGO (the Laser Interferometer Gravitational-Wave Observatory) began to collect data at the rate for which it was designed.

- Even more exciting are plans for a gravitational wave observatory in space, known as LISA (the Laser Interferometric Space Antenna).

Direct detection of dark matter particles is an exciting future possibility, e.g. CDMS (Cryogenic Dark Matter Search) in Minnesota and DAMA (at the Gran Sasso National Laboratories) in Italy.

A great deal of information relevant to cosmology comes from experiments performed here on Earth. One of the deep lessons of modern physics and cosmology is that we can learn a lot about the universe by doing experiments close to home. Ongoing projects include:

- Solar System tests of gravity, especially using satellites traveling to other planets, e.g., the STEP Mission (Satellite Test of the Equivalence Principle).

- Tests of gravity on very small scales—less than 1 millimeter.

- Searches for new weak forces stretching over macroscopic distances.

Most promising of all is the *Large Hadron Collider* (LHC). Becoming operational for the first time in 2007, this is a new machine at the CERN laboratory in Geneva, Switzerland, operating at the high-energy frontier of particle accelerators. It will peer into the regime where we might expect to see the Higgs boson, dark matter candidates, and evidence for or against supersymmetry. Chances are very good that discoveries from the LHC will dramatically alter our ideas about particles and forces and how ordinary matter fits in with dark matter and dark energy. ■

Suggested Reading

As with Lecture 19, the projects described in this lecture are all very new and cutting-edge (as of this writing). Books appear far too slowly to keep up to date with this type of experimental progress. Stay tuned to such journals as *Scientific American* and *Sky & Telescope* for news about the latest progress in experimental physics and observational astronomy.

Questions to Consider

1. Experiments cost money. How should we balance our interests in scientific discoveries against other goals, such as the human exploration of space or the solutions to problems here on Earth?

2. Can you think of any other interesting kinds of experiments, other than the ones described here, that would be relevant to the questions of dark matter and dark energy?

The Past and Future of the Dark Side

Lecture 24

Of course, in the late 1920s, it was realized the universe is not static. Hubble taught us, number one, that some of the nebulae are separate galaxies all by themselves and, number two, that the universe is expanding—that is getting bigger.

Let's recap how we got where we are—a quick historical overview reveals how far we've come in understanding the universe. A century ago, we didn't know how stars burned, that there were other galaxies, or that the universe was expanding. We certainly didn't know anything about dark matter and dark energy. Since then, we've put together a remarkably successful picture of the universe on large scales, as well as a greatly improved understanding of fundamental physics on small scales.

Our current, extremely successful, model of the universe has three basic features. The universe is expanding, and understanding this expansion within the context of general relativity, we can extrapolate all the way back to within one minute of the Big Bang. We live in a smooth, expanding universe that originated in a hot, dense state. Predictions of the Big Bang model, including nucleosynthesis and cosmic microwave background anisotropies, have confirmed the general picture beyond a reasonable doubt.

An inventory of the universe has been pieced together in recent years: 5 percent ordinary matter, 25 percent dark matter, and 70 percent dark energy. Dark matter is cold and (thus far) noninteracting; dark energy is very smoothly distributed and remains nearly constant in density as the universe expands. Again, a wide variety of observations are consistent with this inventory. Finally, we have the story of the growth of structure, from small perturbations at early times into the stars, galaxies, and clusters that we observe today. This picture does not absolutely require a mechanism for generating the perturbations in the first place, but we have one: the inflationary universe scenario.

Why is the universe like it is? Reflecting upon whether or not the current picture of the universe makes sense to us at a deep level—whether it is somehow natural to us—is another way (beyond the experiments discussed in Lecture 23) to think about how we can go beyond our current understanding. A configuration of matter is natural if it's robust; for example, if you move some particles around, you will nonetheless get the same basic outcome. This kind of reasoning is not just philosophizing. It can lead us to very explicit scenarios that help us explain something that we don't otherwise understand. For dark matter, we have scenarios that make dark matter seem very natural. For dark energy, however, we do not have any models that would pass the naturalness test. The simplest model for dark energy, vacuum energy, fits what we see going on only at the cost of an extremely unnatural parameter. The vacuum energy model also does not explain the puzzling coincidence that the amounts of matter and of dark energy are today roughly the same, even though back when the microwave background was formed, the density of dark energy was only one-one billionth of the density of matter.

A configuration of matter is natural if it's robust; for example, if you move some particles around, you will nonetheless get the same basic outcome.

One possible route toward future progress lies in the physics of the dark sector. As far as we can tell at present, dark matter and dark energy interact only through gravity, but the possibility of much richer physics lurks beneath. The dark energy could interact with itself: Rather than being absolutely constant everywhere, it might change slowly with time, it might change slowly with space, and it might have perturbations in its density. The dark matter might interact with itself—in fact, every realistic model of dark matter includes some interactions between the dark matter and itself. Ordinary matter and the dark sector might interact with one another. The dark matter might feel the weak force, or some other force, of ordinary matter. If the dark energy is vacuum energy, then it will not interact, but if the dark energy is dynamical, then we might find interactions between the dark energy and photons, or between the dark energy and nuclear matter. The dark matter and dark energy might interact with one another independently

of ordinary matter. These issues are begging to be addressed experimentally, and a broad-based program is under development to do just that.

It seems as if we know a lot, but we have a lot of unanswered questions. That, of course, is the perfect situation to be in for a scientist! It means that we're not simply flailing in the dark, but much remains to be discovered. The apparently unnatural state of our current universe provokes a dramatic speculation. The most obvious feature of our current universe—so pervasive that we haven't even mentioned it yet—is the difference between the past and the future. Physicists quantify this difference in terms of *entropy*—a measure of disorder that grows inexorably with time. Why was the entropy so small in the early universe, near the Big Bang? Perhaps the answer has something to do with dark energy. Vacuum energy has the property that it keeps space from being completely quiescent; there is always a tiny temperature. If we wait long enough (much longer than the current age of the universe), fluctuations in an otherwise empty space could create a small pocket of dark energy, similar to what is needed to begin inflation. It's conceivable that such an event, in a preexisting universe before our Big Bang, is the origin of everything we see. Such speculation may play a role in helping us understand why the configuration of our current universe looks as though it started in such an unnaturally low state of entropy—this is the kind of speculation we're led to as a result of thinking about dark matter and dark energy.

A century ago, some scientists were convinced that a final codification of the laws of nature was just around the corner. Not everything fit together, but most things did, and the few remaining puzzles were simply details to be ironed out. Those details, of course, grew from minor irritations to major features of our understanding of the universe, as the twin revolutions of relativity and quantum mechanics transformed the way we think about physics. It could be that a similar revolution or two is just around the corner, presaged by the puzzles of dark matter and dark energy. Or perhaps not—there may be quite prosaic explanations for us to settle on. Only further experiments will tell us, and the uncertainly is half the fun. ■

Suggested Reading

Greene, *The Fabric of the Cosmos*, chapters 10–11.

Livio, *The Accelerating Universe*, chapters 7–10.

Vilenkin, *Many Worlds in One*, chapters 16–19.

Questions to Consider

1. Science doesn't "prove" theories rigorously, as mathematics does. How should we judge when a theory is "right enough" to be accepted, as opposed to simply being a tentative hypothesis?

2. What would count, in your mind, as an explanation for why our universe is the way it is?

3. We've learned a lot about cosmology in the last 100 years. What do you think we might learn over the next 100 years?

Exponential Notation

Cosmology and particle physics involve some really big numbers, as well as some really small numbers. Scientists employ an elaborate system of notation and nomenclature to keep track of the quantities that define our universe.

The most important part of this system is **exponential notation**. It's awkward to write out numbers like a trillion, which is 1,000,000,000,000. So instead we just write 10^{12} (read as "ten to the twelfth power," or simply "ten to the twelve"), which represents a one followed by twelve zeroes. A thousand is 10^3, a million is 10^6, a billion is 10^9, and so on. The superscript that keeps track of the number of zeroes is known as the **exponent**, and it can equivalently be thought of as the number of 10s we multiply together to get the quantity under consideration: $10^4 = 10\times10\times10\times10$.

Since 10^0 means that we don't multiply any 10s, it should come as no surprise that $10^0=1$. Decreasing the exponent by one is equivalent to dividing the number by ten. Thus, a number like 10^{-1} stands for one-tenth (one divided by 10), or $10^{-1} = 0.1$. Similarly, $10^{-3} = 0.001$ is one-thousandth, and so forth.

We can express any number at all in exponential notation, just by multiplying an appropriate power of ten by some other number. So a number like 3,500 can equivalently be written as 35×10^2, or (more commonly) as 3.5×10^3. This kind of notation does more than just save ink; it quickly separates out the details about the precise number (the "3.5" part) from the rough idea of the size of the number (the "10^3" part). In cosmology, where numbers are very big and often hard to measure, the exponent is frequently the important part of the number.

Despite the elegance of exponential notation, physicists are people too, and they like to use words. So they've developed a shorthand vocabulary for exponents of various sizes (some of which are familiar from the metric system). "Milli-", for example, means "thousandth," or "times 10–3." A millimeter is 10–3 meters, a milligram is 10–3 grams, and so on. Prefixes you might encounter in particle physics and cosmology include:

peta	tera	giga	mega	kilo	milli	micro	nano	pico	femto
10^{15}	10^{12}	10^{9}	10^{6}	10^{3}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}

peta=1,000,000,000,000,000 femto=.000000000000001

In abbreviations, positive powers of 10 are often written with capital letters, and negative powers with lower-case letters. A mega-electron volt, for example, is an MeV, while a milli-electron volt is an meV. The exception is "kilo-", which is abbreviated with a small "k," as in "km" for "kilometer."

Measuring the Universe

When we measure a physical quantity, we often do it by comparing it to something else. For example, we might observe that a football field is one hundred times longer than a yardstick. Many quantities can be mutually compared; for example, the height of a certain person might also be expressed as a multiple of the length of that yardstick. Other quantities cannot be compared; there's no way of relating the *weight* of that person to the *length* of the yardstick. Quantities that share a common standard of measure are said to have the same units. Extent in space, for example, is expressed in units of length.

The good news is that essentially every quantity in physics can be expressed using some combination of three basic units: **length**, **time**, and **mass**. The understanding of units, sometimes called "dimensional analysis," is actually very useful in physics. However, it is often the first thing that students are exposed to in high-school or college physics courses, which destroys their potential interest in the subject for the rest of their lives.

To make things just a bit more confusing, scientists tend to use different fundamental quantities to express the same kind of units, depending on the situation. We're used to that from our everyday lives; we regularly switch between seconds and minutes and hours and days and weeks (and so forth) to express different lengths of time. In fact, physicists are a bit more parsimonious than that; they tend to measure time using either seconds or years. One year is about 3.16×10^{7} seconds (which many physicists remember as "approximately π times 10^{7} seconds").

Length, of course, is measured in meters, although for mysterious reasons physicists often prefer to use centimeters (10^{-2} meters). In astrophysics, where lengths become quite large, we sometimes use kilometers, but very often revert to **light-years**: a light-year is the distance that light travels in one year, or 9.5×10^{12} kilometers (which is close enough to 10^{13} kilometers for most purposes). You will also frequently find **parsecs**; a parsec is about

3 light-years, or 3.1×10^{13} kilometers, to be precise. (It makes no sense to use parsecs when light-years are a perfectly good unit, but I don't make the rules.)

Mass is measured in grams, or sometimes kilograms. You might think that the non-metric unit for mass is the pound, but that's not quite true. Pounds are units of weight, which is not the same as mass—weight is actually a way of expressing the *force due to gravity* on a certain amount of mass. Of course, as long as we're comparing people and objects that are subject to the same gravitational force, as we usually are here on the surface of the Earth, weight is directly proportional to mass, which is why the concepts get confused. To make a long story short, an object that weighs one pound on the surface of the Earth will have a mass of 454 grams—a bit less than half a kilogram. (In orbit around the earth, the same object would be weightless, but its mass would still be 454 grams.)

Energy has units of velocity squared times mass, where velocity is length divided by time. For sake of convenience, we typically invent a unit to express energy directly, even though in principle we could stick to combinations of the existing units. One **erg** is defined as one gram times (one centimeter squared) divided by (one second squared). You will also come across **joules**; one joule is 10^7 ergs. In particle physics, the most common unit is the **electron volt** (eV), which is 1.6×10^{-12} ergs. The name comes from the amount of energy that an electron gains by being pushed through one volt of electric potential, but you don't have to remember that—it's just a convenient unit in which to measure energies. For example, the energy that binds an electron to a proton to make a single Hydrogen atom is 13.6 eV.

We don't need a separate set of units to measure temperature, because temperature is simply a way of expressing the average kinetic energy of particles in a substance. We nevertheless have several such units, because it's often convenient. Physicists usually use **Kelvins**, which are precisely proportional to energy—one K corresponds to 1.2×10^4 eV. If the particles are perfectly stationary, they have no kinetic energy, and the substance is said to be at **absolute zero**, the lowest possible point of the temperature scale. One Kelvin is exactly equal to one degree Celsius, although the two scales are

related by an offset: zero Kelvin corresponds to –273 degrees Celsius. There are 1.8 familiar Fahrenheit degrees per Kelvin, and absolute zero is –460 degrees Fahrenheit.

There is one twist that seems subtle, but actually makes things much simpler once you get used to it. It makes perfect sense for us to use different units to measure distance and time—you wouldn't think of measuring someone's height using a stopwatch. But relativity teaches us that space and time are really two aspects of a single unified spacetime, so perhaps it's possible to use the same units for both quantities. Indeed it is, because there is one velocity (length divided by time) that has a special status in relativity—the **speed of light**, $c = 3.00\times10^{10}$ centimeters per second. Physicists therefore often find it convenient to measure distance and time in units where the speed of light is set equal to one. For example, if we measure distance in light-years and time in years, we have $c = 1.000$ light-years per year.

The real reason why it's incredibly convenient to use units in which $c = 1$ is because then the units of mass and energy are the same. Remember Einstein's famous formula for the rest energy of an object: $E = mc^2$. When $c = 1$, this is simply $E = m$! So you will very often hear physicists measure mass in what sounds like units of energy. One gram is equivalent to 5.6×10^{32} eV; the mass of the electron is 5.1×10^{5} eV, and the mass of the proton is 9.4×10^{8} eV (about 2,000 times the mass of the electron). This system is so convenient that it becomes second nature to particle physicists.

Nevertheless, we slowly-moving human beings tend to think as time and space as different things. For reference, here are some useful scales of time, length, and mass/energy. In some cases we have given very approximate values, either because the numbers are unknown (such as the mass of the hypothetical WIMP) or because there are a range of values (such as the mass of a typical galaxy). These are denoted by tildes ("~").

Time Scales

Planck time	5.4×10^{-44} sec	
Inflationary Era	$\sim 10^{-35}$ sec	
Electroweak Phase Transition	$\sim 10^{-12}$ sec	
Big Bang Nucleosynthesis	~ 10 sec	
Neutron lifetime (outside a nucleus)	880 sec	
1 day	8.6×10^{4} sec	
1 year	3.2×10^{7} sec	
Human lifetime	$\sim 2\times10^{9}$ sec	
Recombination	1.2×10^{13} sec	$= 3.7\times10^{5}$ y
Age of the universe	4.4×10^{17} sec	$= 1.4\times10^{10}$ y

Length Scales

Planck length	1.6×10^{-33} cm
Proton size	$\sim 10^{-13}$ cm
Atomic size	$\sim 10^{-8}$ cm
Human being	~ 200 cm
Earth radius	6.4×10^{8} cm
Sun radius	7.0×10^{10} cm

Earth-Sun distance	1.5×10^{13} cm	$= 4.9\times10^{-6}$ pc
Distance to nearest star	4.1×10^{18} cm	= 1.3 pc
Size of typical galaxy	$\sim 10^{23}$ cm	$\sim 10^{5}$ pc
Hubble radius	1.3×10^{28} cm	$= 4.2\times10^{9}$ pc

Energy/Mass Scales

Axion mass (hypothesized)	$\sim 10^{-4}$ eV	
Neutrino masses	$\sim 10^{-3}$ eV	
Atomic binding energies	~ 1 eV	$\sim 2\times10^{-33}$ g
Electron mass	0.51 MeV	
Nuclear binding energies	~ 10 MeV	
Proton mass	938 MeV	
Neutron mass	940 MeV	
WIMP mass (hypothesized)	~ 100 GeV	
Planck mass	$\sim 10^{19}$ GeV	$\sim 10^{-5}$ g
Human being	$\sim 4\times10^{28}$ GeV	$\sim 7\times10^{4}$ g
Earth mass	3.4×10^{51} GeV	$= 6.0\times10^{27}$ g
Sun mass	1.1×10^{57} GeV	$= 2.0\times10^{33}$ g
Typical galaxy mass	$\sim 10^{69}$ GeV	$\sim 10^{45}$ g
Energy within observable universe	$\sim 10^{80}$ GeV	$\sim 10^{56}$ g

The Standard Model of Particle Physics

This is a list of the elementary particles in the Standard Model, including the one that has not yet been experimentally discovered (the Higgs boson).

First we group the elementary fermions—the quarks and leptons—into the three "families" or "generations" that particle physicists speak of based on charge and mass.

Table 1. Families/generations of elementary fermions (quarks and leptons)

	Family/generation			
	1st	*2nd*	*3rd*	*charge*
Quarks	up	charm	top	+2/3
	down	strange	bottom	−1/3
Leptons	electron	muon	tau	−1
	electron neutrino	muon neutrino	tau neutrino	0

The next two tables give more detail about properties of elementary fermions, followed by similar information about elementary bosons. We list the mass of each particle, its spin, electrical charge, quark number (Q) and lepton number (L). The masses of the neutrinos are simply listed as "small," because they have not been accurately measured. Quark masses are also highly uncertain, and the values here are approximate.

Table 2. Elementary fermions (quarks)

Quark	Mass	Spin	Charge	*Q, L*
up (*e*)	3 MeV	1/2	+2/3	1, 0
down (*d*)	6 MeV	1/2	−1/3	1, 0
charm (*c*)	1.2 GeV	1/2	+2/3	1, 0
strange (*s*)	100 MeV	1/2	−1/3	1, 0
top (*t*)	171 GeV	1/2	+2/3	1, 0
bottom (*b*)	4.2 GeV	1/2	−1/3	1, 0

Table 3. Elementary fermions (leptons)

Lepton	Mass	Spin	Charge	*Q, L*
electron (e^-)	0.511 MeV	1/2	−1	0, 1
electron neutrino (ν_e)	small	1/2	0	0, 1
muon (μ)	106 MeV	1/2	−1	0, 1
muon neutrino (ν_μ)	small	1/2	0	0, 1
tau (τ)	1.8 GeV	1/2	−1	0, 1
tau neutrino (ν_τ)	small	1/2	0	0, 1

Timeline

The following is a list of important events in the evolution of the universe from the earliest times to the present. We have listed the *time* after the Big Bang, even though we don't know what happens at that moment itself. The *size* of the universe is a relative measure, given (approximately) in terms of the size today. The *temperature* refers to the temperature of the photon background, as well as any kind of particles that are in equilibrium with the photons.

The Planck era

time = 10^{-43} sec

size = 10^{-30}

temperature = 10^{32} Kelvin

This is the era during which quantum gravity is important, and we don't really know what happens. We can't get any closer to the Big Bang at $t = 0$ and say anything with confidence.

Inflation?

time = 10^{-35} sec

size = 10^{-26}

temperature = 10^{28} Kelvin

Theorists have speculated that the very early universe underwent a period of accelerated expansion, known as *inflation*, during which the energy density was temporarily dominated by a form of dark energy at an ultra-high-energy scale. This is a speculative theory, but one that has so far been consistent with observations.

Electroweak phase transition

time = 10^{-12} sec

size = 10^{-15}

temperature = 10^{15} Kelvin

At high temperatures, electromagnetism is unified with the weak interactions. This is the temperature below which they become distinct.

Quark-gluon phase transition

time = 10^{-6} sec

size = 10^{-12}

temperature = 10^{12} Kelvin

Above this temperature, quarks and gluons could exist as independent particles; afterwards, they become bound into the protons and neutrons we see today.

Primordial nucleosynthesis

time = 10 sec

size = 10^{-9}

temperature = 10^{9} Kelvin

The universe cools to a point at which protons and neutrons can combine to form light atomic nuclei, primarily helium, deuterium, and lithium. This is the earliest period about which we can test our understanding of cosmology against observational data.

Recombination

time = 3.7×10^{5} years

size = 10^{-3}

temperature = 3×10^{3} Kelvin

The universe cools to a point at which electrons can combine with nuclei to form atoms, and the universe becomes transparent. Radiation in the cosmic microwave background is a snapshot of this era; tiny fluctuations in temperature, known as *anisotropies*, reveal a great deal about the early universe and its subsequent evolution.

The dark ages

time = 10^8 years

size = 10^{-1}

temperature = 30 Kelvin

Small ripples in the density of matter gradually assemble into stars and galaxies.

Sun and Earth form

time = 9×10^9 years

size = 0.5

temperature = 6 Kelvin

From the existence of heavy elements in the Solar System, we know that the Sun is a second-generation star, formed about 5 billion years ago.

Today

time = 13.7×10^9 years

size = 1

temperature = 2.74 Kelvin

At least 100 billion galaxies shine within the observable universe. Dark energy is beginning to dominate over matter.

Next we list the five types of bosons in the Standard Model. Four of these correspond to the four fundamental forces of nature: the electromagnetic force (the photon); the strong force (eight types of gluons); the weak nuclear force (three bosons: the W+, the W−, and the *Z* bosons); and gravity (the hypothetical graviton). A fifth type of boson (the Higgs boson) is hypothesized to exist in order to explain why fundamental particles can have mass.

Table 4. Elementary bosons (force-carrying particles)

Boson	Mass	Spin	Charge	*Q, L*
photon (γ)	0	1	0	0, 0
gluons (*g*)	0	1	0	0, 0
W^+	80 GeV	1	+1	0, 0
W^-	80 GeV	1	−1	0, 0
Z^0	91 GeV	1	0	0, 0
graviton (*G*)	0*	2	0	0, 0
Higgs (*h*)	100–200 GeV*	0	0	0, 0

*hypothesized values only for the mass of the graviton and of the Higgs boson

The final table lists some of the hadrons, which are composite particles. Hadrons consisting of three quarks are known as baryons: for example, the proton consists of two up quarks and one down, while the neutron consists of two down quarks and one up. Hadrons consisting of a quark-antiquark pair are known as mesons; for example, pions are quark-antiquark pairs.

Table 5. Selected hadrons (baryons)

Baryon	Mass	Spin	Charge	*Q, L*
proton (*p*)	938.3 MeV	1/2	+1	3, 0
neutron (*n*)	939.6 MeV	1/2	0	3, 0

Table 6. Selected hadrons (mesons)

Meson	Mass	Spin	Charge	*Q, L*
positive pion (π^+)	140 MeV	0	+1	0, 0
negative pion (π^-)	140 MeV	0	−1	0, 0
neutral pion (π^0)	135 MeV	0	0	0, 0

The above tables do not include antiparticles, except for the W^+/ W^- and π^+/π^- (which are each other's antiparticles) and those particles that are their own antiparticles (γ, *h*, Z^0, *G*, π^0).

Note: as discussed in the "Measuring the Universe" appendix, particle masses are traditionally given in terms of electron volts (eV), a unit of energy. That's because physicists implicitly multiply by the speed of light squared, using $E = mc^2$, to convert mass into energy. A *mass* of 1 electron volt is equivalent to about 2×10^{-33} grams. Common abbreviations include keV (kilo-eV, or 1,000 eV), MeV (mega-eV, or 1 million eV), and GeV (giga-eV, or 1 billion eV).

Glossary

acceleration of the universe: Distant galaxies have an apparent recession velocity given by Hubble's law. If the velocity is increasing with time, we say that the universe is accelerating. In general relativity, the universe can accelerate only if it is dominated by a persistent negative-pressure component, known as *dark energy*.

anisotropy: *Isotropy* means that things are exactly the same in every direction, and *anisotropy* means that they are slightly different. Our universe is approximately isotropic on large scales but not exactly so; in particular, the tiny anisotropies in the temperature of the cosmic microwave background arise from density perturbations that later grow into galaxies and large-scale structure.

annihilation: What is said to happen when a particle and its antiparticle collide and convert into some other kind of particles.

anthropic principle: The idea that certain features of the universe can be explained by the simple observations that if they were not that way, life could not exist, and we wouldn't be around to measure them.

antimatter: Every particle of matter also has an associated particle of antimatter. The conserved quantities associated with antiparticles (electric charge, quark number, baryon number) are opposite to those of the original particles, but the mass is exactly equal. When a particle has no conserved quantities, such as a photon or Z boson, it is its own antiparticle. When particles and antiparticles collide, they typically annihilate into radiation; for this reason, antimatter is not a good candidate for dark matter. The reason why there is much more matter than antimatter in the universe is an unsolved puzzle; see **baryogenesis**.

atom: The combination of a nucleus and its surrounding electrons. The original use of *atom* by the ancient Greeks referred to the smallest indivisible unit of matter, which is obviously inappropriate for our modern-day atoms.

That's simply because physicists who discovered modern atoms were too hasty in attributing to them the property of being indivisible. It remains true, however, that atoms are the smallest units of individual chemical elements.

axion: A hypothetical boson that is a promising dark matter candidate. Even though axions have very low masses, they are produced at a very low temperature in the early universe, so they would count as *cold* dark matter.

baryogenesis: The hypothetical process in the early universe in which baryons were created preferentially over antibaryons, leading to the preponderance of matter over antimatter in our current universe.

baryon: Any kind of particle with a positive (nonzero) quark number. Protons and neutrons, with three quarks each, are baryons. Antiprotons and antineutrons are antibaryons, although sometimes both types of particles are lumped together as *baryons*. Pions and other mesons, consisting of one quark and one antiquark, have quark number 0; they are hadrons, but not baryons.

baryon number: Quark number divided by 3. Because quarks are confined into colorless combinations, all physical particles have quark numbers that are divisible by 3, which is why baryon number is convenient. Protons and neutrons each have baryon number 1.

Big Bang: The term *Big Bang* has different meanings. It can refer to the hypothetical moment of infinite temperature and density in the early universe, although it is conventionally believed that such a singularity is an artifact of our incomplete understanding of physics in those conditions. Therefore, *Big Bang* is sometimes used to refer to the very earliest moments in the history of the universe, whatever they may have been. Also, the phrase *Big Bang model* is often used to refer to the entire picture of a nearly uniform universe expanding from an initial hot, dense state to its current configuration billions of years later.

Big Crunch: A future singularity of a universe that recollapses. Our universe is accelerating, and there is no evidence that it ever will collapse; however, without a complete understanding of the dark energy, we can't be sure.

Big Rip: A future singularity of a universe that accelerates (not just expands) at an ever-increasing rate. At the Big Rip, the expansion of space tears apart objects, all the way down to individual atoms. We have no reason to believe that our universe will experience a Big Rip, but it is a theoretical possibility.

black hole: A region of spacetime in which the force of gravity is so strong that light itself cannot escape. Particles inside a black hole move inevitably toward the singularity. Black holes can be formed from the collapse of individual stars or, in the form of *supermassive* black holes (greater than a million solar masses), at the centers of galaxies. Such black holes came from ordinary matter so they don't count as dark matter. See also **massive compact halo object**.

blackbody radiation: Any object at a uniform temperature emits photons with a very specific distribution of energies. This is blackbody radiation; in cosmology, the most famous example is the cosmic microwave background, left over from the early universe.

boson: A force-carrying particle, as opposed to a matter particle (fermion). Bosons can be piled on top of each other without limit. Examples include photons, gluons, gravitons, weak bosons, and the Higgs boson. The spin of a boson is always an integer, such as 0, 1, 2, and so on.

bottom quark: An elementary particle, one of the six types of quarks. It is the second-heaviest quark after the top.

brane: Any type of fundamental object that is extended in one or more dimensions. Branes are like particles, except that they can be one-dimensional or two-dimensional (or even more if extra dimensions exist), rather than simply zero-dimensional. A one-dimensional brane is a string, and a two-dimensional brane is a wall (or membrane, from which the term is derived).

brown dwarf star: See **massive compact halo object**.

causal contact: Two particles are said to be in *causal contact* if signals from a common point in the past can reach both of them while traveling at or below the speed of light. Because the universe has a finite age, events can exist that

are outside of causal contact. A period of inflation in the early universe can explain how widely separated points can be in causal contact.

Cepheid variable: A type of pulsating star. The period of pulsation is directly related to the brightness of the star, allowing Cepheids to be used as standard candles.

Chandrasekhar limit: The maximum mass of a white dwarf star, about 1.4 times the mass of the Sun. Above this mass, the gravitational pull becomes too great, and the star must collapse to a neutron star or black hole.

charm quark: An elementary particle; one of the six types of quarks. It is midway in mass between the strange quark and the bottom quark.

classical mechanics: The framework for physics developed by Isaac Newton. In classical mechanics, systems evolve deterministically and can be observed to arbitrarily high precision. Classical mechanics was superseded by quantum mechanics.

cluster: A collection of galaxies orbiting each other under the influence of their mutual gravitational fields.

coincidence scandal: The fact that the energy density in matter and dark energy are roughly comparable in the current universe when we are around to observe them. Dark energy has an approximately constant density, while matter dilutes rapidly as the universe expands; therefore, these two quantities change dramatically with respect to each other. In the early universe, the density of dark energy was much less than that of matter, while in the far future, the situation will be reversed. The fact that we currently live at the point of approximate balance seems to be a coincidence, although it's possible that we will eventually find a deep explanation.

cold dark matter: A kind of dark matter in which the individual particles are moving slowly compared to the speed of light (and always have been). *Hot dark matter*, in contrast, would have rapidly moving particles. Cold dark matter seems to be a much better fit to the data, because hot particles would not be able to collect into galaxies and clusters.

color: Quarks come in three colors, conventionally thought of as red, green, and blue. Antiquarks have anti-colors (anti-red and so on). The color of a quark is the strong-interaction equivalent of the electric charge. A remarkable property of the strong interaction is the confinement of quarks into colorless combinations: either three quarks, one each of red, green, and blue, or one quark and one antiquark.

concordance cosmology: The basic modern cosmological picture, in which the energy density of the universe is approximately 5 percent ordinary matter, 25 percent dark matter, and 70 percent dark energy.

confinement: The strong interaction confines individual quarks (and gluons) into colorless combinations, such as baryons and mesons. The amount of energy that would be required to separate an individual quark is greater than the amount needed to create a new quark/antiquark pair. Therefore, it is impossible to observe quarks all by themselves. At very high energies or temperatures, however, confinement is violated; the early universe was filled with free quarks and gluons.

conserved quantity: A property of individual particles or collections of particles that remains unchanged during any interaction, even as particles change their identities. Electric charge is a classic example. In the Standard Model, other examples include quark number and lepton number; it is possible, however, that unknown physics will eventually be found that violates these quantities.

cosmic microwave background (CMB): Leftover radiation from the Big Bang. The early universe was hot and dense, filled with blackbody radiation at a high temperature. It was also opaque, as photons frequently collided with free electrons. At the moment of recombination, when electrons joined up with protons to make hydrogen atoms, the universe became transparent, and the photons streamed freely through space. They were subsequently redshifted to the microwave portion of the electromagnetic spectrum at an effective temperature of about 2.7 Kelvin. We observe that radiation today as the cosmic microwave background. Tiny deviations in the CMB temperature from place to place provide a snapshot of the universe when it was about

380,000 years old. Those anisotropies arise from fluctuations in the matter density, which have since grown into galaxies and large-scale structure.

cosmological constant: Another name for vacuum energy. Originally introduced by Einstein to help produce static solutions to his equation for the size of the universe but later repudiated by him when Hubble discovered that the universe is expanding. The cosmological constant is now the leading candidate for dark energy.

cosmological constant problem: The puzzle associated with the magnitude of the vacuum energy. Simple arguments lead us to expect a value that is 10^{120} times bigger than what is actually observed. The explanation for this discrepancy is still unknown.

cosmological principle: The idea that the universe is pretty much the same everywhere. In more technical terms, on sufficiently large scales, the universe is homogeneous and isotropic.

critical density: The density that would be required to make the universe spatially flat, as required by the Friedmann equation.

curvature of space: In general relativity, *spacetime* is a four-dimensional manifold, and the curvature of that manifold is what we interpret as gravity. In a homogeneous and isotropic universe, the curvature of *space* alone (which is a subset of the curvature of spacetime) is the same everywhere. It can be zero, in which case, space is flat, and traditional Euclidean geometry is applicable. It can be positive, in which case, space is a three-dimensional version of a sphere. Characteristics of positively curved spaces are that the interior angles of a triangle will always add up to greater than 180 degrees and initially parallel lines will eventually intersect. It can also be negative, analogous to the surface of a saddle. In a negatively curved space, interior angles of a triangle add up to less than 180 degrees and initially parallel lines eventually diverge.

dark energy: A smooth, persistent component of invisible energy, thought to make up about 70 percent of the current energy density of the universe. Dark energy is known to be smooth because it doesn't accumulate preferentially

in galaxies and clusters. Its persistence—the feature that the density of dark energy remains approximately constant as the universe expands—imparts an accelerated expansion to the universe. Evidence for dark energy comes from observations of supernovae that indicate the universe is accelerating and from observations of the cosmic microwave background that measure the total amount of energy in the universe, which turns out to be greater than the energy density in matter (dark and ordinary). The precise nature of the dark energy is not currently understood; it could be a strictly constant vacuum energy or a gradually evolving quintessence field. It is also conceivable that the evidence for dark energy is misleading, and we are really seeing the effects of a departure from Einstein's theory of gravity on very large scales.

dark matter: An invisible, essentially collisionless component of matter that makes up about 25 percent of the energy density of the universe. Ordinary matter made of atoms is about 5 percent of the total energy density, so the dark matter is not simply ordinary matter that is dark; it's a different kind of particle. (Some references use the term *dark matter* to refer to both ordinary matter that is invisible and to this new particle, but that usage has become less frequent.) All candidates in the Standard Model of particle physics have been excluded, so the dark matter particle is something not yet observed in the laboratory.

decay: The spontaneous transformation of a single particle or nucleus into lighter particles. The neutron decays into a proton, an electron, and an electron anti-neutrino, with a lifetime of about 10 minutes. Particles that do not decay are called stable.

density fluctuations: On very large scales, the density of the universe is quite uniform but not perfectly so. From very early times, there were small differences in the amount of matter from place to place, known as *density fluctuations*. Under the influence of gravity, those tiny early fluctuations increased in magnitude as time passed, leading to the formation of galaxies and large-scale structure. Anisotropies in the temperature of the cosmic microwave background provide a precise probe of the properties of density fluctuations at early times.

deuterium: An isotope of hydrogen with 1 proton and 1 neutron in the nucleus.

Doppler effect: The perception on the part of an observer who is moving with respect to a source of light (or sound) that the wavelength is shifted away from that created at the source. If the observer is moving toward the source, the wavelength is shorter (a *blueshift*), while an observer moving away perceives a longer wavelength (a *redshift*). The cosmological redshift is related to the Doppler shift but is not quite the same thing; strictly speaking, it is not due to motions of the galaxies but to the expansion of space in between them.

down quark: An elementary particle; one of the six types of quarks. It is the second lightest quark after the up and, as a constituent of both protons and neutrons, plays an important role in ordinary matter.

Einstein's equation: The fundamental equation (first derived by Einstein) of general relativity. It describes how matter and energy give rise to the curvature of spacetime. In mathematical notation, it reads $R_{\mu\nu} - (1/2)Rg_{\mu\nu} = (8\pi G)T_{\mu\nu}$.On the left-hand side, $R_{\mu\nu} - (1/2)Rg_{\mu\nu}$ is the *Einstein tensor*, a four-by-four matrix characterizing the curvature of spacetime. On the right-hand side, $T_{\mu\nu}$ is the *energy-momentum tensor*, a four-by-four matrix characterizing the matter and energy sources. G is Newton's constant of gravitation.

electric charge: The conserved quantity that acts as a source for the electric field. In natural units, the charge of the electron is –1, the charge of the proton is +1, and the charge of the neutron is 0.

electromagnetism: A triumph of 19th-century physics was the unification of the theories of electricity and magnetism into a unified picture, known as *electromagnetism*. Modern physics views electric fields and magnetic fields as manifestations of a single underlying phenomenon.

electron: An elementary particle; the lightest charged lepton. Electrons are perfectly stable because they are the lightest charged particle of any sort and, therefore, have nothing to decay into. Atoms consist of electrons surrounding

nuclei made of protons and neutrons. Anti-electrons are usually referred to as *positrons*.

electron neutrino: An elementary particle; the neutrino that interacts directly with the electron.

electron volt (eV): A unit of energy. Using $E = mc^2$, 1 electron volt is equivalent to about 2×10^{-33} grams of mass.

electroweak theory: At low energies, the electromagnetic force and the weak nuclear force are very different; most obviously, electromagnetism operates over very large ranges, while the weak force is very short-ranged. At sufficiently high energies, however, these two forces are unified into a single theory.

element: The kind of ordinary matter consisting of atoms with a specific number of protons in the nucleus. Hydrogen is the lightest element, with 1 proton in the nucleus; helium is the next lightest, with 2; and so on. Nuclei with equal numbers of protons but different numbers of neutrons are referred to as different *isotopes* of the same element.

energy density: The amount of energy per volume of space, measured (for example) in units of ergs per cubic centimeter.

equation-of-state parameter: The ratio of the pressure of a fluid to its energy density, often denoted w. The equation-of-state parameter is important in cosmology because it governs the rate at which the energy density evolves as the universe expands. For matter, $w = 0$; for radiation, $w = 1/3$; and for vacuum energy, $w = -1$. The value –1 corresponds to an energy density that doesn't change as the universe expands; if the equation-of-state parameter is slightly higher (such as –0.9), the density slowly decreases, while if it is slightly lower (such as –1.1), the density slowly increases.

equivalence principle: An idea expressing the equivalence of gravity and uniform acceleration. Unlike other forces, gravitation acts on all particles in the same way—any two objects, dropped in a gravitational field, will fall along the same trajectory. Therefore, by doing experiments inside

a sealed room, it is impossible to determine whether the room is sitting in a gravitational field or accelerating through empty space. Einstein was inspired by the equivalence principle to suggest that gravity could be thought of as a feature of the curvature of spacetime, rather than as a separate force propagating through spacetime.

erg: A unit of energy equal to about 600 GeV. Using $E = mc^2$, 1 erg is equivalent to a mass of about 2×10^{-21} grams.

extra dimension: An additional, hidden dimension of space beyond the three that we readily experience. The idea of extra dimensions goes back to Kaluza and Klein, not long after Einstein proposed general relativity. Obviously, such dimensions must be hidden somehow from our view; the conventional method is to imagine that they are compact, with sizes far below what we can observe (perhaps at the Planck scale). Modern ideas use branes to suggest ways that extra dimensions could be substantially larger than that: If all the particles of the Standard Model were confined to a brane, the extra dimensions would be invisible simply because we couldn't get there.

family: See **generation**.

fermion: A matter particle, as opposed to a force particle (boson). Fermions take up space and can't be piled on top of each other. Examples include all varieties of quarks and leptons. The spin of a fermion is always a half-integer (1/2, 3/2, 5/2, and so on).

Feynman diagram: A graphical representation of an interaction between elementary particles. Physicists use Feynman diagrams both as a way to keep track of what processes can occur and as a calculational tool for determining the frequency of such processes.

fifth force: We usually think of four forces in nature: gravity, electromagnetism, the strong nuclear force, and the weak nuclear force. (There is also a force from the Higgs boson, but it has not yet been detected.) Any additional "fifth" force, especially one that operates over long distances, would be evidence for a new light boson, which might be related to the

hypothetical quintessence field. One way to discover such a force is to find that objects of different compositions fall at slightly different rates.

flatness problem: Observations indicate that the spatial curvature of our universe is very close to zero. But in a universe with only matter and radiation (no dark energy), spatial curvature increases with time. The puzzle about why it started so small is the *flatness problem*. **Inflation** is a proposed solution.

flavor: The six different types of quarks are sometimes referred to as *flavors*.

field: A quantity that consists of a number (or set of numbers) at every point in spacetime. The electric field, for example, consists of a vector at every point in spacetime. Modern physics describes all physical particles as vibrations of different kinds of fields—there is an electron field, a gluon field, and so forth. The fact that we observe localized particles rather than smooth fields is a consequence of quantum mechanics.

Friedmann equation: The fundamental equation governing the expansion of the universe in general relativity. The Friedmann equation is a special case of Einstein's equation, applied to a homogeneous and isotropic universe. It relates the Hubble parameter, H, to the energy density, ρ (rho), and the spatial curvature, K. In mathematical notation, it takes the form $(8\pi G/3)\rho = H^2 + K$, where G is Newton's constant of gravitation.

galaxy: A collection of stars, gas, and dark matter, orbiting under their mutual gravitational pull. The galaxy we live in is the Milky Way.

gamma rays: Ultra-high-energy electromagnetic radiation, with wavelengths between 10^{-14} and 10^{-11} meters.

gauge boson: A force-carrying particle of the Standard Model. Examples include photons, gluons, and the W and Z bosons.

general relativity (GR): Einstein's theory of gravitation. The basis of GR is the idea that gravity is the curvature of spacetime. Sources of gravity—

energy, mass, and momentum—are related to spacetime curvature by Einstein's equation. In this curved spacetime background, particles do their best to travel on straight lines, but there are no straight lines because of the curvature. We interpret the resulting motions as being due to the force of gravity.

generation: Both the quarks and the leptons of the Standard Model come in three generations. The lepton generations consist of one charged lepton and its associated neutrino. The lightest generation consists of the electron and the electron neutrino; the next heaviest is the muon and the muon neutrino; and the heaviest is the tau and the tau neutrino. The lightest generation of quarks consists of the up and down quarks; the next generation is the charm and strange quarks; and the heaviest generation is the top and bottom quarks. Generations are sometimes known as *families*. The reason why the same pattern of particles is repeated three times is still not understood.

GeV: Giga-electron volt (1 billion eV). See "Measuring the Universe" appendix.

gluon: The boson that carries the strong nuclear force. There are actually eight different kinds of gluons, representing different combinations of colors and anti-colors. Like quarks, gluons are confined inside hadrons; thus, we don't see individual gluons.

gravitational lensing: The deflection of light by a gravitational field. By measuring the amount of deflection, astronomers can infer the amount of mass in a system.

gravitational wave (gravitational radiation): Oscillating gravitational fields propagating through space at the speed of light. Just as electromagnetic radiation can be caused by an oscillating electric charge, gravitational radiation can be caused by oscillating masses, such as orbiting black holes. Gravitational waves are generally very weak and have not yet been directly observed, although the search for them is actively going on.

gravitino: Hypothetical supersymmetric partner of the (hypothetical) graviton. Given that the Higgs is a boson, the gravitino is a fermion.

graviton: The force-carrying particle for gravity. Individual gravitons have never been observed because of the weakness of the gravitational force. Given that we do not have a consistent theory of quantum gravity, we cannot even be sure that there are such things as gravitons. However, the existence of gravitons seems to be a robust prediction of the most basic features of quantum mechanics and general relativity.

hadron: Any individual particle comprised of quarks and gluons. Hadrons with positive quark number are *baryons*, and those with negative quark number are *antibaryons*. Mesons, consisting of a quark and an antiquark, are hadrons even though they are not baryons.

Heisenberg uncertainty principle: In quantum mechanics, the uncertainty principle places a fundamental limit on the precision with which observers can simultaneously measure the position and velocity of a particle. If the position is measured very precisely, the velocity will be very poorly determined and vice versa. In quantum field theory, the uncertainty principle forbids us from precisely pinning down the state of a field; this uncertainty implies the existence of vacuum fluctuations, in which virtual particles appear and disappear in empty space.

helium: The element with 2 protons. The most common isotope is helium-4, with 2 neutrons.

Higgs boson: A hypothetical boson; the only particle in the Standard Model of Particle Physics that has not yet been detected. The existence of the Higgs boson is predicted by the Higgs mechanism, the process that breaks electroweak symmetry and gives masses to elementary fermions. The Higgs is unstable, with a very short lifetime, and is therefore not a candidate for dark matter.

Higgsino: Hypothetical supersymmetric partner of the (hypothetical) Higgs boson. Given that the Higgs is a boson, the Higgsino is a fermion.

homogeneity: Having the same properties at every point. Homogeneity of the universe means that the density of matter and energy is (approximately) the same on very large scales.

horizon: Because of the finite speed of light and the finite time since the Big Bang, we have access only to a finite region of the universe; other points are out of causal contact with us. The horizon is the point past which no signal can reach us.

horizon problem: In conventional cosmology, if the early universe were dominated exclusively by matter and radiation, widely separated points on the cosmic microwave background were outside each other's horizons. Nevertheless, they appear to be very close in temperature. The horizon problem is simply the puzzle of how points that were never in causal contact could have the same temperature. The most promising solution to this problem is offered by inflation.

hot dark matter: Dark matter that is moving near the speed of light or, at least, was moving near the speed of light in the early days of structure formation. Such particles would not be able to settle into galaxies as efficiently as cold dark matter particles do; the hot dark matter model is, therefore, disfavored.

Hubble constant (Hubble parameter): The ratio of the apparent speed of galaxies to their distances, as encompassed by Hubble's law.

Hubble distance: A rough guide to the size of the observable universe, given by the speed of light divided by the Hubble constant.

Hubble's law: The proportionality between the distance and the apparent recession velocities of galaxies is known as *Hubble's law* ($v = Hd$): The further away a galaxy is, the faster it appears to be receding. (We say *appears* because it's really that space is expanding, not that galaxies are moving through space.) The ratio of the speed to the distance is *Hubble's constant*. Hubble's law doesn't apply exactly to nearby galaxies (where individual motions are important) or to galaxies that are very far away (where the change in the expansion rate over time becomes important).

hydrogen: The element with 1 proton. The most common isotope, it has no neutrons at all; the atomic form consists of just a single proton and a single electron. The isotope deuterium (sometimes called *heavy hydrogen*) contains

a single neutron in the nucleus as well; the unstable isotope tritium contains 2 neutrons.

inflation: A hypothetical period of rapidly accelerated expansion in the very early universe. Inflationary expansion smoothes out space, potentially solving the horizon and flatness problems.

inverse-square law (Newton's law of gravitation): The rule according to which the strength of the gravitational force between two objects decreases as the square of the distance between them increases. Although Newton's understanding of gravitation has been superseded by general relativity, the inverse-square law still holds when gravity is not too strong.

isotope: A nucleus with a specific number of protons and neutrons. Deuterium (1 proton and 1 neutron) and tritium (1 proton and 2 neutrons) are both isotopes of hydrogen, whose most common isotope consists of just a single proton.

isotropy: Looking the same in every direction. The large-scale universe, especially the temperature of the cosmic microwave background, looks very isotropic, although not exactly so. Combining observed isotropy with the cosmological principle implies that the universe is homogeneous.

Kelvin: A unit of temperature; 1 Kelvin is the same as 1° Celsius and is equal to 1.8° Fahrenheit. Zero on the Kelvin scale corresponds to –273° Celsius or –460° Fahrenheit. It is the lowest possible physical temperature, known as *absolute zero*.

keV: Kilo-electron volt (1,000 eV).

kinetic energy: Energy of motion. Kinetic energy stands in contrast to rest energy, which objects have even when they are not moving.

landscape: The hypothetical set of possible phases in which spacetime can find itself, according to string theory. The landscape may have as many as 10^{500} different phases; the precise number is quite uncertain at this time. If

inflation operates to make all these phases actually exist somewhere, we have a multiverse.

lepton: Standard Model fermion that does *not* feel the strong nuclear force. The charged fermions include the electron, the muon, and the tau; each has a corresponding neutrino, which is also a lepton.

lepton number: A conserved quantity given by the total number of leptons minus the total number of antileptons. Electrons, muons, taus, and neutrinos all have lepton number 1; positrons and other antileptons have lepton number –1.

lifetime: The average time an unstable particle will last until it decays.

light cone: The set of points in spacetime that can be reached from a given event by traveling at the speed of light. The *future light cone* is the set of points that can be reached by traveling from the fixed event, while the *past light cone* is the set of points from which the fixed event can be reached. Because nothing can travel faster than the speed of light, the only points that can ever be influenced by some event are those within that event's future light cone. Similarly, the only points that can ever influence that event are those that are within its past light cone.

light-year: Distance traveled by light in one year, about 9×10^{12} kilometers.

lightest supersymmetric particle (LSP): In supersymmetry, the hypothetical lightest superpartner of the known Standard Model particles. Because supersymmetric particles have not yet been experimentally discovered, we don't yet know which superparticle is the LSP. If it is neutral and stable, the LSP makes an ideal WIMP candidate for dark matter.

lithium: The element with 3 protons. The most common isotope is lithium-7, with 4 neutrons.

mass: In relativity, the *mass* of a particle is simply a measure of the energy it has when it is at rest. Using $E = mc^2$, physicists convert readily between energy and mass and will often make such statements as "The mass of the

electron is 511,000 electron volts," even though the electron volt is a unit of energy. What they mean is, if you multiply the mass of the electron by the speed of light squared, you get an energy equal to that many electron volts.

massive compact halo object (MACHO): A dim star or planet-like object. MACHOs can range in size from brown dwarf stars to massive planets or could even be black holes. Although they are dark, they count as ordinary matter rather than as part of the dark matter.

matter: This term has different meanings in different contexts. In particle physics, we distinguish *matter particles* (fermions, which take up space) from *force particles* (bosons, which can pile on top of each other). In cosmology, *matter* refers to any collection of slowly moving particles (where *slow* is a comparison with the speed of light). We then have *ordinary matter* or *dark matter*. The energy of slowly moving particles is approximately equal to their rest energy, which is a constant. Therefore, the energy density in matter is proportional to the number density, which declines as the volume goes up.

meson: A composite bosonic particle consisting of one quark and one antiquark. Mesons are hadrons (given that they are made of quarks), but they are not hadrons (given that their total quark number is 0).

MeV: Mega-electron volt (1 million eV). See the "Measuring the Universe" appendix.

microlensing: Minor occurrences of gravitational lensing, when a dim star or planet passes in front of a brighter star. The gravitational field of the lensing object deflects away some of the brighter object's light, leading to a temporary dimming in brightness, even if no distortion in shape or position is observed.

Milky Way: The galaxy in which we live, consisting of about 100 billion stars.

modified Newtonian dynamics (MOND): A model of gravity in which the gravitational force falls off more slowly at large distances (small accelerations) than in conventional Newtonian gravity. Originally inspired

by the dynamics of spiral galaxies, MOND does a pretty good job at fitting individual galaxies but fails when applied to clusters and has nothing to say about the expansion of the universe.

multiverse: The hypothetical concept of unobservable regions of space where conditions are potentially very different from those we see in our observable universe. The "other universes" may be truly separate from ours or simply too far away to be accessible. The multiverse, with its wide variety of conditions, plays an important role in the anthropic principle.

muon: An elementary particle; a lepton similar to the electron but heavier and unstable. The discovery of the muon in 1936 was the first evidence of the second generation of elementary particles.

muon neutrino: An elementary particle; the neutrino that interacts directly with the muon.

nebula (pl.: nebulae): Originally, a nebula was simply a celestial object that appeared fuzzy in telescopes, as opposed to pointlike stars. It was later realized that some nebulae are collections of gas and dust within our galaxy, while others are separate galaxies in their own right.

neutron: A composite fermionic particle consisting of two down quarks and one up quark. Neutrons are both hadrons and baryons. The neutron has electric charge 0, quark number +3, and lepton number 0. It decays into a proton, an electron, and an electron anti-neutrino, with a lifetime of about 10 minutes.

neutrino: An elementary fermionic particle. Neutrinos are uncharged leptons and come in three flavors: the electron neutrino, the muon neutrino, and the tau neutrino. Electron neutrinos interact directly with electrons but not with muons or taus, and so forth. Although they are much less massive than any of the quarks or charged leptons, it was recently discovered that neutrinos do have small nonzero masses.

neutron star: A type of compact star consisting of (almost) nothing but neutrons. Neutron stars are formed when the mass of a white dwarf is greater

than the Chandrasekhar limit, and gravity forces the electrons and protons to combine into neutrons.

Newton's law of gravitation: See **inverse-square law**.

nucleon: Protons and neutrons are collectively known as *nucleons* because they make up the atomic nucleus.

nucleosynthesis: The process by which heavy elements are formed from lighter ones. Primordial nucleosynthesis occurred when the universe was a few minutes old, and protons and neutrons were converted into hydrogen, deuterium, helium, and lithium. Heavier elements are formed in stars and supernova explosions in the later universe.

nucleus (pl.: nuclei): A bound collection of protons and neutrons. Nuclei have a positive electric charge (from their protons) and generally capture electrons to form atoms.

ordinary matter: Matter consisting of particles in the Standard Model of Particle Physics—which includes every kind of matter ever directly observed (so far). In the current universe, about 5 percent of the total density takes the form of ordinary matter. It is sometimes referred to as *baryonic matter*, because the large majority of the mass density of ordinary matter comes in the form of baryons (protons and neutrons in atomic nuclei).

parallax: The change in apparent position of a distant (but not too distant) object when you look at it from two different places. The further away something is, the smaller its parallax; this effect, therefore, provides an excellent way to determine the distances to astronomical objects. Unfortunately, the parallax of objects outside our galaxy is too small to be observed, and we must rely on less direct distance indicators.

Pauli exclusion principle: The impossibility of putting two fermions into the same state. It is this property of fermions that makes them matter particles—they take up space. Bosons, in contrast, do not obey the exclusion principle and can be squeezed together without limit.

phantom energy: A hypothetical form of dark energy, in which the energy density is gradually increasing as the universe expands. If such an increase continues in perpetuity, the future of the universe can experience a Big Rip.

photino: Hypothetical supersymmetric partner of the photon. Given that the photon is a boson, the photino is a fermion.

photon: The bosonic particle that mediates the electromagnetic force. An electromagnetic wave or field consists of a condensate of a large number of photons. Photons interact directly with any kind of particle that carries electric charge.

pion: A composite meson consisting of one quark and one antiquark. There are three types of pions: positively charged, negatively charged, and neutral. Pions may be thought of as the particles carrying the force that keeps protons and neutrons together inside the nucleus.

Planck scale: The scale at which quantum gravity is presumed to become important. In different contexts, *Planck scale* can refer to the Planck energy (roughly 10^{28} eV), the Planck mass (roughly 10^{-5} g), the Planck length (roughly 10^{-33} cm), or the Planck time (roughly 10^{-43} s).

positron: The antiparticle of the electron.

pressure: If you have a gas in a box, the force per unit area exerted by the gas on the sides of the box is the pressure. In the middle of the box, the net force is 0, because it is pushing equally in all directions, but the pressure is still there. In cosmology, there is no box, but the gravitational effect of the pressure of different cosmological fluids is very important. Matter (slowly moving particles) has approximately 0 pressure; radiation (particles moving near or at the speed of light) has a pressure that is 1/3 of its energy density; and vacuum energy has a pressure that is exactly the opposite of its energy density ($p = -\rho$). Thus, if the vacuum energy is positive, its associated pressure is negative, sometimes known as *tension*.

proton: A composite fermionic particle consisting of two up quarks and one down quark. Protons are both hadrons and baryons. The proton has

electric charge +1, quark number +3, and lepton number 0. As the lightest particle with a nonzero quark number, it appears to be stable, although it is conceivable that protons have a lifetime that is very large but not infinite (if quark number is not precisely conserved).

quantum chromodynamics (QCD): The theory that explains the strong nuclear force in terms of quarks and gluons. In QCD, the quantity that plays a role analogous to electric charge is color, which gives rise to the name *chromodynamics*. Just as photons couple to electric charge, gluons couple to color. According to QCD, color is confined inside hadrons, so that observable particles are always colorless combinations of quarks.

quantum electrodynamics (QED): The quantum theory of electricity and magnetism. QED describes electromagnetic forces as arising from the exchange of photons, which couple to electric charge.

quantum field theory: As you might guess, the quantum-mechanical theory of fields. In classical field theory, fields stretching through space obey deterministic equations of motion and can be precisely measured. In quantum field theory, the state of the field is contained in a wavefunction that describes the probability of observing the field in a given configuration. If the fluctuations in the field are very small, they will appear to observers as individual particles. If the fluctuations are large (which can happen only for bosonic fields as a result of the Pauli exclusion principle), they can be observed as macroscopic classical fields, such as electromagnetism and gravity.

quantum gravity: The hoped-for reconciliation of quantum mechanics and general relativity. Although the particles and forces described by the Standard Model of Particle Physics fit comfortably into the framework of quantum mechanics, it is much more difficult to describe gravity (a manifestation of the curvature of spacetime itself, according to general relativity) in quantum terms. The leading candidate for a consistent theory of quantum gravity is string theory.

quantum mechanics: The framework for physics, developed in the first half of the 20th century, in which physical systems are described by *wavefunctions* that determine the likelihood of obtaining various observational results.

In quantum mechanics, as opposed to classical mechanics, the outcomes of experiments are necessarily probabilistic, rather than deterministic. A consequence of quantum mechanics is the Heisenberg uncertainty principle, which states that we cannot simultaneously fix the position and velocity of an object to arbitrary precision.

quantum number: Another name for a conserved quantity.

quark: Standard Model fermion that does feel the strong nuclear force. The six types include the up, down, charm, strange, top, and bottom quarks.

quark number: A conserved quantity given by the total number of quarks minus the total number of antiquarks. The quark number is 1/3 of the baryon number. Protons and neutrons have quark number 3; mesons have quark number 0, because they consist of one quark and one antiquark.

quintessence: A hypothetical dynamical field constituting the dark energy. Quintessence, which would feature a slowly changing energy density as the field evolves, is an alternative to vacuum energy, which would be strictly constant.

radiation: To a cosmologist, *radiation* is any collection of particles that move at or close to the speed of light. Examples would include photons (electromagnetic radiation) and gravitons (gravitational radiation). Neutrinos, which are very low mass, act as radiation in the early universe when the temperature is high but eventually cool down and behave like matter (slowly moving particles). The energy density in radiation diminishes more quickly than that in matter as the universe expands, because every individual particle loses energy due to the redshift.

radio waves: Electromagnetic waves with long wavelengths (anywhere from 1 millimeter up to 100,000 kilometers). An important example in cosmology is microwaves, with wavelengths of a few millimeters.

recombination: The moment in cosmological history when electrons combined with protons (and other nuclei) once and for all, about 380,000 years after the Big Bang. Before recombination, the universe was opaque, and

afterward, it was transparent. The cosmic microwave background provides a snapshot of what conditions were like at the moment of recombination.

redshift: The stretching of the radiation from shorter to longer wavelengths as the universe expands. The cosmological redshift, caused by the expansion of space, is similar to the Doppler effect, but there are important conceptual differences.

rest energy: The energy a particle has when it is not moving. The rest energy is simply the mass of the particle times the speed of light squared ($E = mc^2$).

rotation curve: The velocity of gas and stars orbiting a galaxy, considered as a function of their distance from the galactic center. Ordinarily, the velocity of orbiting particles decreases at large distances from a gravitating object, because the force due to gravity becomes weaker. In spiral galaxies, however, the rotation speeds tend to remain constant, rather than decreasing—a phenomenon known as *flat rotation curves*. This is taken as evidence that there is additional unseen mass in the galaxies, interpreted as dark matter.

scale factor: The quantity that characterizes the relative size of the universe as it expands, often denoted $a(t)$. If the scale factor doubles in size, it means that the distance between galaxies has grown by a factor of 2.

selectron: Hypothetical supersymmetric partner of the electron. Given that the electron is a fermion, the selectron is a boson.

singularity: A point of infinite spacetime curvature. In general relativity, singularities appear inside black holes and at the Big Bang or Big Crunch. Many physicists believe that a true theory of quantum gravity will resolve such singularities and that the real world is completely nonsingular.

slepton: Hypothetical supersymmetric partner of the lepton. Given that leptons are fermions, sleptons are bosons. Each type of lepton has its corresponding slepton; for example, the superpartner of the tau is the stau.

spacetime: The four-dimensional manifold describing the universe. Relativity took the separate Newtonian concepts of three-dimensional absolute space

and one-dimensional absolute time and replaced them with four-dimensional spacetime. The division of spacetime into "space" and "time" will not look the same to all observers. In general relativity, spacetime can be curved, and that curvature manifests itself as gravity.

spatial curvature: See **curvature of space**.

special relativity (SR): Einstein's theory of the unification of space and time into a single concept of spacetime. It is based on the idea that the speed of light is an absolute maximum velocity that looks the same to all observers. According to SR, the elapsed time along a trajectory is not the same for all paths connecting two events but depends on the route taken through spacetime.

speed of light: Usually denoted c, the speed of light in a vacuum is the maximum velocity at which two objects can pass by each other. (In general relativity, the relative velocity of two distant objects is not well defined.) It is approximately equal to 300,000 kilometers per second. Light travels at slower speeds when it moves through a medium such as air or glass; however, the phrase *speed of light* generally refers to the speed in a vacuum.

spin: An intrinsic amount of angular momentum generally characteristic of elementary particles.

squark: Hypothetical supersymmetric partner of the quark. Given that quarks are fermions, squarks are bosons. Each type of quark has its corresponding squark; for example, the superpartner of the top quark is the stop squark.

stable: Particles are stable if they would last forever if left by themselves.

standard candles: Objects of known brightness at astronomical distances; useful as distance indicators. If we know how bright an object really is and how bright it appears we can figure out how far away it must be.

Standard Model of Particle Physics: The modern theory of elementary particles and their interactions. The Standard Model includes 12 kinds of fermions—6 kinds of leptons and 6 kinds of quarks—and 3 types of gauge

bosons that mediate forces between them. It also includes the Higgs boson, which has not yet been discovered. It does not, strictly speaking, include gravity, although it's often convenient to include gravitons among the known particles of nature.

strange quark: An elementary particle; one of the six types of quarks. It is somewhat heavier than the up and down quarks and, therefore, plays only a minor role in ordinary matter. To be honest, not that strange, as quarks go.

string theory: The idea that the elementary constituents of matter are small loops of string rather than pointlike particles. String theory was originally suggested as a theory of the strong interactions (before QCD was invented) but inevitably predicted the existence of a particle with all the characteristics of the graviton. These days, we think of string theory as a candidate theory of quantum gravity. Unfortunately, it has proven difficult to derive explicit testable predictions from the theory that can be compared with experiment.

strong lensing: Gravitational lensing that is strong enough to create multiple images of lensed objects.

strong nuclear force: The force that binds quarks together in hadrons. It is mediated by gluons, as described by quantum chromodynamics. The strong force between two quarks actually grows stronger as the quarks are pulled apart, which leads to the effect of confinement.

Sunyaev-Zeldovich (SZ) effect: When low-energy photons from the cosmic microwave background pass through the hot gas in a cluster of galaxies, they can be scattered to higher energies. This is the *Sunyaev-Zeldovich effect*, which can be observed by mapping the energies of CMB photons in the direction of clusters on the sky. The SZ effect is similar to a shadow being cast on the CMB.

supernova (pl.: supernovae): An exploding star. A particular type of supernova, known as *Type Ia*, plays an important role in cosmology because it is a standardizable candle. Type Ia supernovae arise when enough mass accretes onto a white dwarf star to pass the Chandrasekhar limit. The white

dwarf then collapses, and the outer layers are expelled in a violent explosion, almost as bright as an entire galaxy.

superpartner: In supersymmetry, the hypothetical particles associated with the particles that are already known in the Standard Model; superpartners of fermions are bosons, and superpartners of bosons are fermions. For example, the superpartner of the electron is the selectron, and the superpartner of the photon is the photino.

superstring: Strings (as in string theory) that are also supersymmetric. It is widely believed that string theory must be supersymmetric to describe the real world.

supersymmetry: A hypothetical symmetry relating bosons to fermions. If supersymmetry exists in the real world, it must be broken, so that the partners of the known Standard Model particles are too heavy to have yet been discovered. The lightest such particle, if it's neutral and stable, makes an excellent dark matter candidate.

symmetry breaking: The situation that is said to exist when the symmetry of a theory is hidden from view by the dynamics of a system. In the electroweak sector of the Standard Model of Particle Physics, the Higgs field acts to break the electroweak symmetry. If supersymmetry is part of the real world, some unknown mechanism must act to break it as well, because superpartners with the same mass as ordinary particles are not observed in nature.

tau: An elementary particle; the heaviest charged lepton. The tau has a very short lifetime, as it rapidly decays into lighter leptons.

tau neutrino: An elementary particle; the neutrino that interacts directly with the tau.

temperature: A measure of the average kinetic energy of particles in a system. As the universe expands, the temperature tends to decrease as the reciprocal of the scale factor.

tension: Negative pressure. If a substance pulls things together, like a stretched rubber band, it has a tension. Dark energy has tension but (apparently paradoxically) makes galaxies accelerate away from each other. That's because the important effect is not directly from the tension but through its gravitational influence. The direct pull of the tension is exactly the same in every direction and, therefore, cancels out.

top quark: An elementary particle; one of the six types of quarks. The top is the heaviest quark.

unstable: Particles that decay when left by themselves are unstable.

up quark: An elementary particle; one of the six types of quarks. It is the lightest quark and, as a constituent of both protons and neutrons, plays an important role in ordinary matter.

vacuum: The most common meaning of *vacuum* is simply "empty space." It can also refer to the lowest energy state of a physical system.

vacuum energy: The energy density of empty space, also known as the cosmological constant. The vacuum energy is not caused by a dynamical field but is a property of spacetime itself—the minimum amount of energy that can possibly exist in some region of space. It is, therefore, constant throughout space and time and, in particular, does not diminish as the universe expands. Vacuum energy is a leading candidate for the dark energy.

vacuum fluctuations: According to the Heisenberg uncertainty principle, quantum fields will inevitably fluctuate, even in empty space. These vacuum fluctuations take the form of virtual particles rapidly popping in and out of existence. The energy of the vacuum fluctuations is an important contributor to the vacuum energy.

virtual particle: A particle that briefly fluctuates into existence, then disappears as a result of the inherent uncertainty in quantum mechanics.

***W* boson**: Charged force-carrying particles of the weak interactions. Unlike the photon (which carries the electromagnetic force), *W* bosons are very massive, explaining why the weak force operates only over short ranges.

wavefunction: The function in quantum mechanics that encodes the state of a physical system. The wavefunction provides the information necessary to calculate the probability of obtaining any specific answer when the system is observed—for example, the position or velocity of a particle. It is impossible to observe a generic wavefunction without changing the quantum state of the system; this is the origin of the Heisenberg uncertainty principle.

weak lensing: Gravitational lensing that is strong enough to distort images of objects but not strong enough to break them into multiple images. Given that we usually don't know the original shape of the images, the effects of weak lensing can only measured statistically, by observing many objects in one region.

weak nuclear force: The short-range, relatively feeble force carried by the *W* and *Z* bosons. The weak force is responsible for certain important radioactive decays, such as the decay of the neutron. At high energies, it combines with electromagnetism to form the electroweak interaction.

weakly interacting massive particle (WIMP): A candidate particle for dark matter. The phrase *weakly interacting* in this context doesn't simply mean that the particle doesn't interact very much; it refers specifically to the weak nuclear force of the Standard Model. Massive, stable particles that interact through the weak force and not through the strong force or electromagnetism turn out to naturally have an appropriate relic density to make up the dark matter. A good example of a WIMP candidate is the lightest supersymmetric particle (LSP).

white dwarf: A star that has used up all its nuclear fuel. White dwarfs are supported by the pressure from their electrons, which cannot be squeezed too tightly because of the Pauli exclusion principle.

X-rays: High-energy electromagnetic radiation, with wavelengths between 10^{-11} and 10^{-8} meters.

***Z* boson**: Neutral force-carrying particle of the weak interactions. Unlike the photon (which carries the electromagnetic force), *Z* bosons are very massive, explaining why the weak force operates only over short ranges.

Einstein, Albert (1879–1955). German-American physicist. Einstein is, of course, the one physicist everyone can name. His fame is well deserved; when he was chosen as *Time* magazine's "Person of the Century," it was hard to argue with the choice.

In 1905 Einstein was two years out of school and working at the patent office in Zurich, unable to find an academic job. That year, he published a series of papers that revolutionized modern physics, among which was the first comprehensive statement of the principles of special relativity. This theory replaced Newtonian mechanics and fit elegantly with Maxwell's laws of electricity and magnetism. It was not, however, compatible with Newton's theory of gravity. For the next 10 years, Einstein worked to reconcile gravity with relativity, culminating in the formulation of general relativity in 1915. In 1919, a British team led by Arthur Eddington took observations during a total eclipse that confirmed general relativity's prediction of light-bending due to the gravitational field of the Sun, making Einstein an international celebrity.

Einstein was never comfortable with the apparent loss of determinism implied by quantum mechanics (even though some of his work helped found the field). In his later years, he worked on an ultimately unsuccessful program to unify gravitation and electromagnetism; this attempt caused him to drift away from the mainstream of physics at the time, but it foreshadowed later successes at unifying the forces. In 1932, just before Hitler was elected chancellor of Germany, Einstein moved permanently to the United States. He became active in politics, helping to urge President Franklin Roosevelt to develop the atomic bomb and, in 1952, declining an offer to become Israel's second president.

Freedman, Wendy (b. 1957). American astronomer. First to accurately measure the Hubble constant. Freedman received her Ph.D. in 1984 from the University of Toronto. Since then, she has worked at the Carnegie Observatories in Pasadena, California, where she now serves as director. She

was the principal investigator for one of the primary missions of the Hubble Space Telescope Key Project to determine the Hubble constant. For decades after Hubble's original discovery, astronomers had struggled to determine the numerical value of the constant relating the distance of a galaxy to its apparent recession velocity; it's this number that sets the scale for the size and age of the observable universe. Freedman and her collaborators were able to establish that the Hubble constant is approximately 72 kilometers per second per megaparsec: For each megaparsec of distance, a galaxy will be receding at 72 km/sec.

Friedmann, Alexander (1888–1925). Russian physicist. Friedmann was the first person to systematically study cosmology in the context of general relativity and, in 1922, derived the Friedmann equation for the evolution of the universe. Like many famous figures in the history of general relativity, he fought in World War I. Friedmann died young, of typhoid fever. One of his students, George Gamow, became an influential theoretical physicist and cosmologist.

Galilei, Galileo (1564–1642). Italian physicist. The first person to understand conservation of momentum and universality of free fall. Also the first to use a telescope for astronomical observations and provide evidence that the Earth moves around the Sun. Galileo, it is safe to say, was at least the grandfather of modern physics (if Newton was the father).

Born in Pisa, Galileo briefly studied medicine before switching to mathematics, in which he became a lecturer at the University of Pisa in 1589; in 1592, he moved to the University of Padua. He was an extraordinary source of new ideas and experiments. A short list of his accomplishments in physics would include the discovery that the period of a pendulum is independent of its amplitude, a demonstration that the distance an object falls is proportional to the square of the time of its fall, an attempted measurement of the speed of light, a demonstration that objects of different compositions fall at the same rate, and (most importantly) the realization that moving objects which are not acted on by any force will retain their velocity. In 1609, Galileo built his first telescope and immediately turned it on the night sky. He found the first evidence for the rings of Saturn; showed that Venus had phases, just as the Moon does; and discovered the satellites of Jupiter. This last finding was the

first example of celestial bodies that clearly orbited an object other than the Earth, calling into question the geocentric Ptolemaic system.

In 1611, Galileo visited Rome to demonstrate some of his discoveries to Church authorities. Although initially supportive, the Church ultimately asked him to treat the heliocentric model of Copernicus as merely a useful hypothesis rather than as a true representation of reality. But in 1623, Galileo's friend Cardinal Barberini was elected pope, which encouraged Galileo to publish a book on the controversy. In these dialogues, he gave the job of defending geocentrism to the character Simplicio, which the pope took as public ridicule. In 1633, Galileo was convicted of heresy and put under house arrest, where he stayed until his death. He had two daughters and one son out of wedlock; the daughters were sent to a convent in Arcetri, where they remained for their entire lives.

Gamow, George (1904–1968). Ukranian-American physicist. Gamow is responsible for much of our modern understanding of the early universe in the context of the Big Bang model. His early career took him from Odessa (Ukraine) to Leningrad (Russia) to Göttingen (Germany) to Copenhagen (Denmark) to Cambridge (England), before returning to the Soviet Union. His student years coincided with the birth of quantum mechanics, and Gamow made a significant contribution to the field, being the first to understand the process of radioactive decay as the result of quantum tunneling.

In 1933, Gamow and his wife defected from the USSR, and in 1934, they moved to the United States for good. With his students Ralph Alpher and Robert Herman, Gamow wrote a series of papers in the 1940s and 1950s that laid out the early history of the universe in the Big Bang theory. These included the process of Big Bang nucleosynthesis and the formation of the cosmic microwave background, including a rough prediction of its temperature. Later in life, Gamow made important contributions to the theory of DNA and wrote a series of extremely successful popular books on science, including *One, Two, Three…Infinity* and the *Mr. Tompkins* series.

Guth, Alan (b. 1947). American physicist. Inventor of the theory of cosmic inflation. Born in New Jersey, Guth skipped his senior year of high school to attend the Massachusetts Institute of Technology. He stayed on at MIT for

his doctorate, working on the theory of quarks. After getting his Ph.D., Guth took on a series of postdocs; he was unable to land a faculty position because he hadn't published many papers. But he gradually became interested in questions of cosmology and, in 1980, had a spectacular realization: Many problems of the conventional cosmological model could be solved in a single swoop by postulating a period of accelerated expansion in the first fraction of a second in the history of the universe. His theory of cosmic inflation caused a sensation, and he was swiftly offered a professorship back at MIT, where he is still teaching today. The research notebook recording the flash of insight in which Guth first understood the implications of inflation is currently on display at the Adler Planetarium in Chicago.

Hubble, Edwin (1889–1953). American astronomer. Showed that many nebulae were galaxies in their own right ("the universe is big") and established that the universe is expanding ("and it's getting bigger"). Hubble graduated with a bachelor's degree in 1910 from the University of Chicago, where he stood out more as an athlete than as a student. He then went to Oxford as a Rhodes Scholar, where he studied jurisprudence and Spanish. Returning to the United States, he worked as a lawyer and as a high school teacher and basketball coach before serving in World War I. After the war, he returned to the University of Chicago, earning a Ph.D. in astronomy in 1917.

Hubble was offered a position at the newly created Mount Wilson Observatory in California, where he stayed for the rest of his life. Using the 100-inch Hooker telescope, by 1925, he was able to identify individual pulsating Cepheid stars in Andromeda and other "nebulae," proving that they were actually galaxies like the Milky Way. Hubble and Milton Humason then combined their measurements of distances with redshift data obtained by Vesto Slipher to establish that more distant galaxies appeared to be receding more rapidly. This result, announced in 1929, can be interpreted in the context of general relativity as arising from the expansion of the universe. Hubble never won the Nobel Prize; during his lifetime, astronomy was not considered to fall under the category of physics for purposes of the prize.

Lemaître, Georges-Henri (1894–1966). Belgian priest and physicist. Lemaître was the first person to take seriously the initial cosmological

singularity—what we now call the Big Bang, which he referred to as the "Cosmic Egg" or the "Primeval Atom." Friedmann was the first to derive the equations governing the expansion of the universe in general relativity, but Lemaître's 1927 paper derived Hubble's law on theoretical grounds and emphasized the singular beginning of the universe. It wasn't until 1929 that Hubble and Humason would demonstrate that the universe really is expanding.

Lemaître led a colorful life. His studies were interrupted so that he could serve in the Belgian army in World War I. Afterward, he simultaneously studied physics and prepared for the priesthood. His studies took him to the University of Cambridge (England), Harvard, and the Massachusetts Institute of Technology. After Hubble and Humason's discovery, Lemaître popularized his Primeval Atom theory in lectures in Britain and the United States and became a well-known figure. Later in life, he became president of the Pontifical Academy of Sciences and served on the Second Vatican Council.

Mather, John (b. 1946). American astrophysicist. Performed the first precision measurement of the blackbody nature of the cosmic microwave background. Mather was an undergraduate at Swarthmore College and received his Ph.D. from Berkeley. He worked for a while at Columbia University before moving to NASA's Goddard Space Flight Center. It was at Columbia, in 1974, that he first began working on the plans for what would eventually become the Cosmic Background Explorer (COBE) satellite, which was ultimately launched in 1989. Mather was the lead investigator for the mission as a whole and for the Far Infrared Spectrophotometer (FIRAS) instrument, which measured the CMB spectrum. He shared the Nobel Prize in Physics in 2006 with George Smoot.

Newton, Isaac (1643–1727). British physicist. Inventor of classical mechanics, calculus, and the inverse-square law of gravity and, perhaps, the greatest scientist of all time. Newton attended Cambridge University, where he became fascinated with the modern ideas of such thinkers as Descartes and Galileo. Several of Newton's discoveries—such as the inverse-square law of gravity, a design for a new kind of telescope, and the separation of white light into its component colors using a prism—would have individually

been enough to grant him scientific immortality. But they pale in comparison to his invention of calculus—arguably the most important advance in the history of mathematics—and to his formulation of classical mechanics and the laws of motion—arguably the most important advance in the history of physics. These accomplishments were not without controversy; calculus, in particular, was the subject of a decades-long priority dispute with German mathematician Gottfried Leibniz. Newton probably did his work first but didn't publish until after Leibniz.

Classical mechanics, first published as part of Newton's *Principia Mathematica*, formed a basis for physics that is still taught to students today. It consists of Newton's three laws of motion: Objects in uniform motion stay in uniform motion unless acted on by an outside force; force equals mass times acceleration; and for every action, there is an equal and opposite reaction. These rules were ultimately superseded by the laws of relativity and quantum mechanics but were precise enough to land astronauts on the Moon. To gauge the scale of Newton's accomplishment, in *Blind Watchers of the Sky*, Rocky Kolb compares it to the Wright brothers putting together a modern jumbo jet and flying it from Kitty Hawk to New York. Together with his law of gravity, Newton was able to use the laws of classical mechanics to derive Kepler's laws of planetary motion.

Newton never married and is thought to have died a virgin. Along with his scientific studies, he managed to have a career in public life, serving briefly as a member of Parliament and for an extended time as master of the Royal Mint. He used this latter position to persecute his enemies, of which he had many. He also moved England to the gold standard in 1717. He performed considerable experiments in alchemy and spent much of his later years publishing extensively on religion.

Penzias, Arno (b. 1933). American astrophysicist. Co-discoverer (with Robert Wilson) of the cosmic microwave background. Penzias was born in Germany; like many other Jewish families, he and his parents fled when Hitler came to power, and he became an American citizen in 1946. After getting his Ph.D. from Columbia, he moved to Bell Labs in New Jersey, where he worked on the emerging field of radio astronomy. Penzias and Wilson constructed an ultra-sensitive radiometer but encountered a

mysterious source of background noise that they could not account for. They ultimately realized that it was cosmic in origin and learned that a group in nearby Princeton was searching for exactly this radiation. Penzias and Wilson shared the Nobel Prize in 1978 with Pyotr Kapitsa, a Russian physicist who discovered the phenomenon of superfluidity.

Perlmutter, Saul (b. 1959). American astronomer. Leader of the Supernova Cosmology Project, one of the two teams to discover the acceleration of the universe. Perlmutter was an undergraduate at Harvard and earned his Ph.D. at Berkeley under the supervision of Richard Muller. His thesis project centered on the development of a robotic telescope that searched for supernovae. After it became clear that Type Ia supernovae could be used as distance indicators, Perlmutter and Carl Pennypacker launched a project to search for supernovae in wide-field images of thousands of galaxies at a time. This effort grew into the Supernova Cosmology Project, which by 1994 was gathering supernovae by the bunches. Perlmutter was awarded the Shaw Prize along with Adam Riess and Brian Schmidt in 2006 for their discovery of the acceleration of the universe. Perlmutter is currently a scientist at Lawrence Berkeley Laboratory and a professor at the University of California, Berkley.

Riess, Adam (b. 1969). American astronomer. Member of the High-Redshift Supernova Team, one of the two teams to discover the acceleration of the universe. Born in Washington, DC, Riess was an undergraduate at MIT before moving to Harvard for graduate school. Like Brian Schmidt, he worked with Robert Kirshner on using supernovae to measure the Hubble constant; his Ph.D. thesis received the Trumpler Award for the most influential dissertation in astrophysics. While working as a postdoc at Berkeley, Riess was the lead author on the first paper to announce that the universe is accelerating. He was awarded the Shaw Prize along with Brian Schmidt and Saul Perlmutter in 2006 for their discovery of the acceleration of the universe. He is currently a scientist at the Space Telescope Science Institute in Baltimore.

Rubin, Vera (b. 1928). American astronomer. Discovered dark matter in spiral galaxies. When she applied to Swarthmore as a high school student intending to study science, she was told by an admissions officer that she might be better off pursuing her interests in art, perhaps by painting pictures of astronomical objects; she chose to attend Vassar instead. Rubin tried

to attend Princeton for her master's degree, but Princeton didn't admit women into the graduate school at the time, so she went to Cornell instead. In 1954, she obtained a Ph.D. from Georgetown, where George Gamow was her supervisor. In 2005, Princeton eventually made up for its mistake, awarding her an honorary doctorate, which she has also received from Harvard and Yale.

After graduation, Rubin continued on at Georgetown as a researcher and faculty member, before moving to the Department of Terrestrial Magnetism at the Carnegie Institution in 1965. In the 1970s, she undertook an ambitious program, frequently in collaboration with Kent Ford, to study the rotation of nearby spiral galaxies. Rubin demonstrated conclusively that gas in the outer regions of galaxies was moving much faster than could be accounted for by the gravitational field of the visible matter alone, providing strong evidence for the existence of dark matter. She was awarded the National Medal of Science in 1993.

Schmidt, Brian (b. 1967). American-Australian astronomer. Leader of the High-Redshift Supernova Team, one of the two teams to discover the acceleration of the universe. After growing up in Montana and Alaska, Schmidt attended Harvard for his graduate work, where he wrote a thesis on using supernovae to measure the Hubble constant under the supervision of Robert Kirshner. After moving to Mount Stromlo and Siding Springs Observatories in Australia, Schmidt put together a team to discover large numbers of supernovae and use them to learn about cosmology. He was awarded the Shaw Prize along with Adam Riess and Saul Perlmutter in 2006 for their discovery of the acceleration of the universe.

(Full disclosure: Your humble lecturer was officemates with Schmidt in graduate school and can vouch that Brian is a gourmet cook as well as a world-class astronomer.)

Smoot, George (b. 1945). American astrophysicist. Discoverer of temperature anisotropies in the cosmic microwave background. Smoot obtained both his undergraduate and graduate degrees at MIT. Originally interested in particle physics, he switched to cosmology, perceiving it to be a less crowded field. After moving to Berkeley, he began to study the microwave background. In

1977, he discovered a slight anisotropy in the temperature of the CMB, but this was due to the motion of the Milky Way galaxy through space, not to primordial fluctuations. Smoot was the lead investigator on the Differential Microwave Radiometer (DMR) experiment on the Cosmic Background Explorer (COBE) satellite, launched in 1989. It was this project that, in 1992, announced the discovery of primordial temperature fluctuations from which large-scale structure in the universe ultimately evolved. In 2006, Smoot shared the Nobel Prize in Physics with John Mather, leader of the COBE team.

Wilson, Robert (b. 1936). American astrophysicist. Co-discoverer (with Arno Penzias) of the cosmic microwave background. Wilson was an undergraduate at Rice University and received his first patent the summer after he graduated, before moving to Caltech for his Ph.D. work. In 1963, he joined Bell Labs in New Jersey, where he began collaborating with Penzias on radio instrumentation. After the discovery of the CMB in 1965, Wilson continued to work on radio astronomy, mapping out organic molecules in the Milky Way. Penzias and Wilson shared the Nobel Prize in 1978 with Pyotr Kapitsa, a Russian physicist who discovered the phenomenon of superfluidity.

Zwicky, Fritz (1898–1974). Swiss-American astrophysicist. First to propose the concept of dark matter. Born in Bulgaria to Swiss parents and educated in Switzerland, Zwicky moved to the United States in 1925 to take a position at Caltech, where he remained for the rest of his life. In 1933, his analysis of the dynamics of the Coma cluster of galaxies led to the surprising discovery that there was much more matter in the cluster than implied by the visible gas and stars. Zwicky and Walter Baade coined the term *supernova*, and Zwicky was personally responsible for the discovery of more than 100 supernovae. He also did pioneering early work on the theory of neutron stars, cosmic rays, and gravitational lenses.

Bibliography

A large number of great books have been written about cosmology, particle physics, and gravity. None of them follows this course precisely, especially because these are fast-moving fields in which discoveries keep coming at us unexpectedly. But all the books listed here are good reads at an accessible level and will help flesh out the ideas discussed in the lectures.

Recommended Readings:

Cole, K. C. *The Hole in the Universe: How Scientists Peered over the Edge of Emptiness and Found Everything*. San Diego, CA: Harcourt, 2001. A far-ranging look at the concept of "nothing" in physics, including the energy of empty space.

Ferris, Timothy. *The Whole Shebang*. New York: Simon and Schuster, 1997. An in-depth account of modern cosmology, its practitioners, and its implications.

Feynman, Richard. *The Character of Physical Law*. Cambridge, MA: MIT Press, 1965. A brief introduction to the way the laws of physics work, by someone who understood them as well as anyone.

Freeman, Ken, and Geoff McNamara. *In Search of Dark Matter*. New York: Springer Praxis Books, 2006. A nice, short overview of the dark matter problem. Explains in detail how we weigh galaxies and how we distinguish ordinary baryonic matter from exotic dark matter.

Goldsmith, Donald. *The Runaway Universe: The Race to Find the Future of the Cosmos*. Cambridge, MA: Perseus, 2000. A brisk report of the 1998 discovery of the accelerating universe by two supernova cosmology teams and its aftermath.

Greene, Brian. *The Fabric of the Cosmos*. New York: Knopf, 2004. A modern survey of space, time, and gravity, from Einstein's relativity to modern cosmology and superstring theory.

Guth, Alan. *The Inflationary Universe*. Cambridge, MA: Perseus, 1998. A masterful account of modern cosmology, especially the early universe, from the inventor of the inflationary universe scenario.

Hogan, Craig. *The Little Book of the Big Bang*. New York: Copernicus, 1998. Just what the title promises—a short and engaging survey of the basic picture of Big Bang cosmology.

Kirshner, Robert. *The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos*. Princeton, NJ: Princeton University Press, 2002. A first-person account of one astronomer's research on supernovae, culminating in the discovery that the universe is accelerating.

Kolb, Rocky. *Blind Watchers of the Sky*. Reading, MA: Addison-Wesley, 1996. A gripping history of cosmology, told through biographical sketches of its leading lights.

Lemonick, Michael. *Echo of the Big Bang*. Princeton, NJ: Princeton University Press, 2003. A behind-the-scenes look at the development and launch of the WMAP satellite and what we learned from its observations of the cosmic microwave background.

Levin, Janna. *How the Universe Got Its Spots*. Princeton, NJ: Princeton University Press, 2002. A highly personal and fascinating story of one young researcher's investigations into black holes and the topology of the universe.

Livio, Mario. *The Accelerating Universe: Infinite Expansion, the Cosmological Constant, and the Beauty of the Cosmos*. New York: Wiley, 2000. A short book on the beauty of modern cosmology and its connections to the arts.

Nicolson, Ian. *The Dark Side of the Universe: Dark Matter, Dark Energy, and the Fate of the Cosmos*. Baltimore, MD: Johns Hopkins University Press,

2007. A recent book that focuses on dark energy; includes a large number of color photos.

Osserman, Robert. *Poetry of the Universe*. Garden City, NJ: Anchor Books, 1995. An accessible introduction to cosmology from the perspective of a mathematician.

Overbye, Dennis. *Lonely Hearts of the Cosmos*. New York: Harper Collins, 1991. The story of modern cosmology, told in an engaging and personal style.

Randall, Lisa. *Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions*. New York: Ecco, 2005. A recent, in-depth examination of the idea of extra dimensions by one of the field's leading innovators.

Vilenkin, Alex. *Many Worlds in One: The Search for Other Universes*. New York: Hill and Wang, 2006. An investigation of the consequences of the possibility that our universe is just one of many.

Wald, Robert. *Space, Time, and Gravity*. Chicago: University of Chicago Press, 1992. A short, slightly technical introduction to Einstein's theories of special and general relativity originally published in 1977, with a revised and updated edition that appeared in 1992.

Weinberg, Steven. *Dreams of a Final Theory*. New York: Pantheon, 1992. An examination of modern particle physics, with an emphasis on the role of fundamental theory and the virtues of reductionism.

———. *The First Three Minutes*. New York: Basic Books, 1977. Slightly out of date but still a classic exposition of early-universe cosmology by a Nobel laureate.

Will, Clifford. *Was Einstein Right?* New York: Basic Books, 1993. A valuable look at alternatives to Einstein's theory of general relativity and the experimental tests to which modern physics subjects them.

Internet Resources (Web sites for general tutorials, as well as updated news items):

American Institute of Physics. *Cosmic Journey*. A well-constructed site that provides an introduction to modern cosmology, as well as a historical survey. There are also discussions of the instruments used by astronomers from early times to the present. http://www.aip.org/history/cosmology/.

Carroll, Sean. *Cosmology Primer*. A brief overview of the basics of modern cosmology, from observations of large-scale structure and the microwave background to the very early universe. http://preposterousuniverse.com/writings/cosmologyprimer/.

Contemporary Physics Education Project. *The Universe Adventure*. A companion to *The Particle Adventure* (below), this interactive site introduces the basic ideas of Big Bang cosmology at an accessible level. http://www.cpepweb.org/main_universe/universe.html.

Cosmic Variance Blog. An informal Web log with Sean Carroll and several other contributors. All the authors are physicists and astronomers, and conversations range from science news to whatever else crosses their minds. http://cosmicvariance.com/.

Feuerbacher, Björn, and Ryan Scranton. *Evidence for the Big Bang*. A highly detailed but accessible overview of the many pieces of evidence we have in favor of the basic Big Bang picture. Includes detailed refutations of many common skeptical arguments. http://www.talkorigins.org/faqs/astronomy/bigbang.html.

Lawrence Berkeley National Laboratory. *The Particle Adventure*. An interactive site that provides a basic introduction to particle physics. A detailed tutorial is accompanied by numerous links to associated resources. http://particleadventure.org/.

NASA. *Cosmology 101*. A site associated with the WMAP cosmic microwave background satellite but also including an introduction to basic cosmology. http://map.gsfc.nasa.gov/m_uni.html.

Space Telescope Science Institute. *The Hubble Site*. A public site associated with the Hubble Space Telescope (HST). Includes news about astronomy in general and HST in particular, as well as a breathtaking image gallery and explanations of Hubble's many breakthroughs. http://hubblesite.org/.

Wright, Edward L. *Ned Wright's Cosmology Tutorial*. A tutorial at a slightly higher level than many of the previous sites. Uses basic algebra, as well as detailed presentations of modern astronomical data. www.astro.ucla.edu/~wright/cosmolog.htm.